Queensland University of Technology
Brisbane Australia

This may be the author's version of a work that was submitted/accepted for publication in the following source:

Chalmers, Christina, Carter, Merilyn, Cooper, Tom, & Nason, Rod
(2017)
Implementing 'big ideas' to advance the teaching and learning of science, technology, engineering, and mathematics (STEM).
International Journal of Science and Mathematics Education, *15*(S1), pp. 25-43.

This file was downloaded from: https://eprints.qut.edu.au/103304/

© Consult author(s) regarding copyright matters

This work is covered by copyright. Unless the document is being made available under a Creative Commons Licence, you must assume that re-use is limited to personal use and that permission from the copyright owner must be obtained for all other uses. If the document is available under a Creative Commons License (or other specified license) then refer to the Licence for details of permitted re-use. It is a condition of access that users recognise and abide by the legal requirements associated with these rights. If you believe that this work infringes copyright please provide details by email to qut.copyright@qut.edu.au

Notice: *Please note that this document may not be the Version of Record (i.e. published version) of the work. Author manuscript versions (as Submitted for peer review or as Accepted for publication after peer review) can be identified by an absence of publisher branding and/or typeset appearance. If there is any doubt, please refer to the published source.*

https://doi.org/10.1007/s10763-017-9799-1

Implementing "big ideas" to advance the teaching and learning of science, technology, engineering, and mathematics (STEM)

Christina Chalmers, Merilyn (Lyn) Carter, Tom Cooper, and Rod Nason

Queensland University of Technology, Brisbane, Australia

Abstract

Although education experts are increasingly advocating the incorporation of integrated STEM curriculum units to address limitations in much current STEM teaching and learning, a review of the literature reveals that more often than not such curriculum units are not mediating the construction of in-depth STEM knowledge. In this paper, we conjecture that the challenge of generating integrated STEM curriculum units that overcome this limitation and facilitate in-depth learning of and about STEM can be met by the use of three types of big ideas: *within-discipline big ideas that have application in other STEM disciplines*, *cross-discipline big ideas*, and *encompassing big ideas*. We provide a six-component framework (together with an example of the framework in action) that can be used to scaffold pre- and in-service teachers' development of integrated STEM curriculum units based around these types of big ideas. The paper concludes by discussing possible directions for future research and development in this field.

Keywords: big ideas, integration, STEM, themes

In recent years, most OECD countries have been developing "new" STEM education programs. The vision implicit in most of these programs is one where rigorous academic concepts are coupled with real-world lessons as all students apply science, technology, engineering, and mathematics in contexts that not only better reflect the multidisciplinary and interdisciplinary nature of the work of most current STEM professionals (Lantz, 2009; Wang, Moore, Roehrig, & Park, 2011) but also make connections between school, community, and work (Tsupros, Kohler, & Hallinen, 2009). Most of these programs also place a strong emphasis on establishing relationships between the STEM disciplines with the objective of expanding people’s critical and creative thinking skills (Siekmann, 2016).

A review of the literature indicates this vision is far from being realized. More often than not, layers of “technology” and “engineering” are merely being grafted onto standard science and mathematics curricula; also, despite the inclusion of engineering concepts and processes in many current science and technology curricula (e.g., Australian Curriculum, Assessment and Reporting Authority, 2013b, 2013c; Next Generation Science Standards [NGSS] Lead States, 2013) science, technology, engineering, and mathematics often are still being compartmentalized into “silos” (Lantz, 2009; Moore et al., 2014).

In order for STEM education to address these issues, there has been a movement towards integrated STEM curriculum (Education Council, 2015; Honey, Pearson, & Schweingruber, 2014; Johnson, Peters-Burton, & Moore, 2016). Comprehensive perspectives on STEM integration where different forms of boundary crossing are displayed along a continuum of increasing levels of integration, with progression along the continuum involving greater interconnection and interdependence among the disciplines, have been produced in recent years (e.g., Kelley & Knowles, 2016; Moore et al., 2014; Vasquez, Sneider, & Comer, 2013). However, despite the guidance provided by these perspectives, the goal of designing integrated STEM curriculum units that facilitate in-depth learning of and about STEM is challenging (Berland, 2013; English, 2016; Honey et al., 2014).

Poorly conceptualized integrated STEM curriculum units have the potential to undermine in-depth student learning (National Academy of Engineering, 2014). For example, in many integrated STEM curricula students do not engage in the construction of in-depth mathematics, engineering, and science concepts (Berland, 2013; English, 2016; Pruett, 2015).

There is also the problem of the individual components of STEM within integrated STEM curriculum units, particularly mathematics and engineering, being "dumbed down" as the teaching focus moves from knowledge construction to application (Cooper, 2014; English, 2016).

In this paper, we conjecture that the challenge of generating integrated STEM curriculum units that facilitate in-depth learning of and about STEM can to a large extent be met by a six-component framework based on the use of a continuum of STEM big ideas: *within-discipline big ideas that have application in other disciplines* (e.g., scale, ratio, proportion, energy) ←→ *cross-discipline big ideas* (e.g., variables, patterns, models, computational thinking, reasoning and argument, transformations) ←→ *encompassing big ideas* (e.g., conservation, systems, coding, relationships, change, representations). The paper begins with a review of the literature about why STEM big ideas should be used. Following this, the proposed six-component framework based on the continuum of STEM big ideas for scaffolding the design of integrated STEM curriculum units that facilitate in-depth learning of and about STEM is presented. This framework is presented as a "work-in-progress" with the aim of advancing theory and practice in integrated STEM education.

Why Big Ideas?

The notion of big ideas in STEM education is not new but has in recent years been afforded some prominence (e.g., Askew, 2013; Cooper, 2014; Harlen, 2010; Hurst, 2015; Michaels, Shouse, & Schweingruber, 2007; Schoenfeld, 2016; Sneider, 2010). Big ideas refer to key ideas that link numerous discipline understandings into coherent wholes (Charles, 2005; Harlen, 2010). Such ideas are central to the understanding *of* and *about* STEM across a wide range of fields and taken together represent models of our world as provided by the STEM disciplines (Harlen, 2010; STEM-Ed Scotland, 2010).

Within big ideas of STEM, it is possible to identify two complementary and interdependent categories: *content big ideas* and *process big ideas*. Content big ideas can be *concepts* (e.g., space, time, and force; addition, subtraction, multiplication, and division; constraints, optimization, and feedback), *principles* (e.g., inverse principle), *theories* (e.g., atomic theory, chaos theory), *strategies* (e.g., design trade-off, top-down design and bottom-up design strategies; problem-solving strategies) or *models* (e.g., set models, number line models, probabilistic models) (Cooper, 2014; Harlen, 2010; Hurst, 2015; Sneider, 2010). Process big ideas (e.g., observing, experimenting, controlling variables, formulating hypotheses, interpreting data) are the intellectual skills associated with the acquisition and effective use of content knowledge (Australian Curriculum, Assessment and Reporting Authority, 2013b).

Big ideas *about* STEM focus on the nature and discourse of STEM, that is the “habits of mind” of participants in STEM communities of practice and how they create, evaluate, and advance knowledge (Harlen, 2010). “Habits of mind” are sets of dispositions or ways of thinking that describe how professional practitioners in given STEM fields seek to understand the world; these habits of mind become an interpretive lens through which the practitioners view and seek solutions to complex problems (Gurung & Hayne, 2009). Big ideas about STEM usually are more abstract and global in nature than big ideas *of* STEM. This is exemplified by the four following examples: (a) Scientific knowledge is tentative, empirically based, theory driven, and based on human inference, imagination, and creativity (Khishfe & Lederman, 2006); (b) Technology is a process with activities that include designing, making, and using technology (Kelley & Knowles, 2016); (c) Engineering design is both iterative and systematic (Sneider, 2010); and (d) Mathematics is about seeking patterns and relationships based on underlying structures and relationships (Cooper, 2014).

Much support for the educational efficacy of incorporating big ideas of and about STEM into the design of curriculum emanates from cognitive science. Within the field of cognitive science, it has been known for many years that the understanding of big ideas: (a) leads to more flexible and generalizable knowledge use, (b) improves problem-solving, (c) makes it easier to make sense of and master new facts and procedures, and (d) facilitates transfer of knowledge (Niemi, Vallone, & Vendlinski, 2006). These findings come from a variety of cognitive science sources such as schema theory research and studies of experts and novices (e.g., Chi, Glaser, & Farr, 1988; Glaser, 1983; Richland, Stigler, & Holyoak, 2012).

Further support for the educational efficacy of incorporating big ideas into the design of curriculum comes from research in the interrelated fields of cognitive constructivism (Bruner, 1960; Piaget, 1985) and social constructivism (Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991; Palincsar, 1998; Vygotsky, 1978). Many pedagogical approaches derived from constructivist theories place much emphasis on big ideas (e.g., Bereiter & Scardamalia, 2010; Grennon Brooks & Brooks, 1993). In Bereiter and Scardamalia's (2010) knowledge-building environments, participants engage in a collaborative process of intentionally constructing cognitive artefacts (i.e., big ideas) to advance the current understanding of individuals and the collective understanding of the group. Grennon Brooks and Brooks' (1993) pedagogical approach builds on the cognitive constructivist theories of Piaget and Bruner. One of their central tenets is that: "constructivist teachers structure lessons around big ideas, not small bits of information. Exposing students to wholes first helps them determine the relevant parts as they refine their understandings of the wholes" (Brooks & Grennon Brooks, 1999, p. 20).

Epistemological as well as learning development grounds have been proffered to justify the inclusion of big ideas in STEM education curriculum. This is well exemplified in the field of mathematics education by Fosnot (2007) and Cooper (2014). Both Fosnot and Cooper place much emphasis on the structures of mathematics. To them, big ideas are “the central, organizing ideas of mathematics—principles that define mathematical order” (Schifter & Fosnot, 1993, p. 35). Building on the learning development work of Piaget, Fosnot argued for a focus on big ideas because she believed that they can play a crucial role in the developmental journey along a landscape of learning mathematics. According to Fosnot, big ideas are not only deeply connected to the structures of mathematics but also characteristic of shifts in learners’ reasoning—shifts in perspective, in logic, in the mathematical relationships they set up. As such, they are connected to part-whole relations and to the structure of thought in general (Piaget, 1977). Building on the work of Glaser (1983) and other schema theorists, Cooper argued that big ideas can be: (a) topic generic (i.e., they apply across topic areas—they have some generic capabilities with respect to topics and are not restricted to a particular domain); (b) level generic (i.e., they apply across year levels—they have the capacity to remain meaningful and useful as a learner moves up the grades); and (c) content generic (i.e., their meaning is independent of context and content—it is encapsulated in what they are and how they relate, not the particular context in which they operate). Thus he suggested that big ideas should be incorporated into mathematics curriculum for the following reasons: (a) power (i.e., one big idea can be applied in many areas of mathematics); (b) efficiency (i.e., there are many fewer big ideas in mathematics than there are procedures and rules to be rote learned); and (c) organic growth (i.e., as they are applied to topics, big ideas build structural connectivity in mathematics that constructs knowledge as a rich schema that can easily accommodate the next steps in mathematics knowledge and makes later learning of mathematics easier).

Ontological grounds for the inclusion of big ideas in STEM education curriculum also have been proffered. Many seminal thinkers in the field of STEM education (e.g., Cuoco, Goldenberg, & Mark, 2010; Harlen, 2010; Kelley & Knowles, 2016; Schoenfeld, 2016;

Sneider, 2010) are arguing that students need to be inducted into STEM disciplines' habits of mind and ways of thinking in order to understand the nature and discourse of STEM and thus be able to legitimately engage in STEM. For example, Harlen noted that, because science is a multifaceted discipline encompassing knowledge about the world and the processes of finding that knowledge, "what we want learners to understand includes the processes of scientific activity as well as the ideas to which it has led" (Harlen, 2010, p. 20). Kelley and Knowles (2016) and Sneider (2010) argued for the inclusion of the following three "habits of mind" big ideas in their visions of technology/engineering education: (a) systems thinking (a way of approaching problems used by engineers); (b) desire to encourage and support effective team work (a hallmark of capable engineering work, since no single individual is likely to bring to a problem situation all of the necessary knowledge and skills for a good solution); and (c) concern for the societal and environmental impacts of technology (technology and engineering work involves personal values as well as knowledge and skills). Schoenfeld (2016, p. 10) argues that "students should have opportunities to learn important mathematical content and practices, *and to develop productive mathematical habits of mind* [emphasis added]."

Another reason proffered for the inclusion of big ideas is that they may help to resolve the tension between coverage and depth (Charles, 2005; Harlen, 2010; Hurst, 2015; Hurst & Hurrell, 2014; Metz, 2012; Siemon, Bleckly, & Neal, 2012). When faced with the task of implementing curriculum documents which often present content in a traditional linear and compartmentalized manner (Hurst, 2015), teachers have to decide how to make best use of limited and precious learning time. Science educators such as Harlen (2010) and Metz (2012), technology/engineering educators such as Sneider (2010), and mathematics educators such as Hurst (Hurst, 2015; Hurst & Hurrell, 2014), Charles (2005), and Siemon et al. (2012) have suggested that part of the solution to this dilemma is to conceive the goals of STEM education not in terms of bodies of knowledge, processes and skills but instead as a progression towards key ideas which together enable understanding of events and phenomena of relevance to students’ lives during and beyond their school years.

Big Ideas and Integrated STEM Curriculum Units

Most of the literature with respect to STEM big ideas has focused predominantly on the within-discipline application of big ideas. However, in recent years STEM educators have begun to focus increasingly on cross-discipline applications of STEM big ideas. This research indicates that the challenge of generating integrated STEM curriculum units that facilitate in-depth learning of and about STEM can to a large extent be met by the use of a continuum of STEM big ideas: *within-discipline big ideas that have application in other disciplines* ←→ *cross-discipline big ideas* ←→ *encompassing big ideas.*

Within-discipline big ideas that have application in other disciplines

The appropriate application of within-discipline big ideas in the contexts of other STEM disciplines that enables the big ideas to become more meaningful and relevant to the students can mediate the generation of *context-integrated STEM curriculum units* (Moore et al., 2014). Good examples of context-integrated STEM curriculum units are provided by Silk, Higashi, Shoop, and Schunn (2010), Puntambekar & Kolodner (2005), and Fortus, Krajcik, Dershimer, Marx, and Mamlok-Naaman (2005). In their Robot Synchronized Dancing unit, Silk et al. (2010) situated the learning of proportional reasoning (a mathematics big idea) in the technology/engineering context of a robotics design problem. In a similar vein, in many of the context-integrated STEM curriculum units generated by the developers of the Learning by Design (LBD) approach (Puntambekar & Kolodner, 2005) and the Design-Based Science (DBS) approach (Fortus et al., 2005), the learning of science big ideas was situated in the context of designing technology/engineering artefacts.

A review of the literature reveals that context-integrated STEM curriculum in which within-discipline big ideas are meaningfully applied in the contexts of other STEM disciplines can have at least two important outcomes. First, in addition to extending a discipline’s knowledge into the problems of another domain (Silk, 2011), it also facilitates increased student conceptual understanding, interest and motivation, and transfer of knowledge (Czerniak & Johnson, 2014). For example, Silk et al. (2010) found that their context-integrated STEM curriculum unit enhanced student learning of proportion whilst at the same time helping the students to progress beyond trial-and-error design strategies. Embedding science big ideas in design problems in a manner similar to the LBD or DBS approaches has been found to enhance the learning of science by providing students with opportunities for scientific inquiry and the application of what they learned to the development of a solution (Daugherty, 2012). Second, it also has been found that context-integrated STEM curriculum units can facilitate deepening the learner’s capacity for complex and creative problem-solving (Marshall, 2010) by helping them to develop capabilities that enable them to respond to familiar and unfamiliar situations and to make informed decisions and solve problems efficiently (Hefty, 2015; King, 2014).

Cross-discipline big ideas

Cross-discipline big ideas (e.g., variables, patterns, models, computational thinking, reasoning and argument, transformations, nature of proof) are content or process ideas located in two or more STEM disciplines. Because these big ideas have application across two or more domains of STEM knowledge, they can provide educators with the means to go beyond STEM “silos” and design and implement curriculum units that meaningfully integrate science, technology, engineering, and mathematics (Chalmers & Nason, in press; Gomez-Zweip, 2016; Hurst, 2015; NGSS Lead States, 2013).

Vagla (2016) has classified the use of cross-discipline big ideas as a *conceptual theme approach* to STEM integration. She claims that this approach is a most effective way of facilitating the inclusion of discipline-based standards in meaningful, relevant, and genuine ways within integrated STEM curriculum units, especially within the middle school.

In addition to identifying similarities across the different STEM disciplines, cross-discipline big ideas can do much to improve the quality of teaching/learning when used in integrated STEM curriculum by also helping students to identify the differences between STEM disciplines (Moore et al., 2014; NGSS Lead States, 2013). Although the ways in which many cross-discipline big ideas are defined and used in the different STEM disciplines are very similar, they are not identical. This can be illustrated by the example of a cross-discipline big idea about STEM, the *notion of proof*. The notion of proof is an important aspect of mathematical and scientific thinking. In both disciplines, a concept may be initially developed from empirical observations leading by an inductive process to the identification of a pattern, which is described in a statement called a *conjecture* in mathematics or a *theory* in science. The statement is likely to be tested to determine if it can be falsified, since one counter-example is sufficient for nullification. In mathematics, if the conjecture withstands falsification, the next step would usually be a deductive process leading to a proof (albeit one that is consistent with the underlying axioms that are assumed to be true). In science (and in some aspects of mathematics) where no amount of confirming empirical evidence can prove a theory, its acceptance is probabilistic, relying on an inability to find a counter-example, appropriate use of scientific method and sufficient supporting evidence as to eliminate alternative theories. Thus, mathematicians talk of conjectures and proof, while scientists rely on theories and acceptance. According to Moore et al. (2014), by first acknowledging the differences between the ways a cross-discipline big idea are defined and used in the different STEM disciplines, and then helping students to make the connections between these differences, teachers can support the development of deep conceptual understanding. Moore et al. argued that this should help students develop more sophisticated understandings of each discipline individually, and STEM as a whole.

Encompassing big ideas

A review of the literature reveals two categories of encompassing big ideas can be used to mediate the generation of integrated STEM curriculum units that facilitate in-depth learning of and about STEM: *conceptual encompassing big ideas* and *content encompassing big ideas*.

Conceptual encompassing big ideas (e.g., representations, conservation, systems, coding, relationships, change) are superordinate STEM concepts, principles, theories, strategies or models shared across the STEM disciplines that not only subsume but also enable one to integrate and build upon sets of more localized/specific STEM big ideas. For example, subsumed under the umbrella of representations are physical artefacts (manipulatives), symbols, tables, graphs, diagrams, and models (e.g., numerals in mathematics, tables and graphs in science, algorithms in technology, and scale drawings in engineering). Students often do not make connections between representations at the between-discipline level. For example, a teacher of senior biology said to one of the authors, “The other day I had to teach my Year 11 students how to draw a column graph. I would not have had a problem with this, except that I am also their math teacher and I have just finished teaching them about graphs in math.” A more encompassing viewpoint about the notion of representations, emphasizing similarities and differences between how specific types of representations are used in science and mathematics, may have assisted these students in making the connections between their biology and mathematics lessons.

In addition to facilitating the making of connections between the STEM disciplines, conceptual encompassing big ideas can also mediate in-depth learning by facilitating a more multi-layered and in-depth investigation of a problem/challenge during the course of an integrated STEM curriculum (Bratzel, 2009). This can be illustrated by referring to an integrated STEM unit in which students were presented with the following challenge: *Design a car that can climb as steep a mountain as possible but also be able to cross the valley quickly*. To go beyond trial-and-error design strategies to resolve this challenge, students are required to engage with big ideas such as gears, speed and torque (physics), ratios and proportion (mathematics), and the engineering big ideas such as the engineering design process (EDP) and trade-offs (i.e., compromising on individual goals to make the overall product work better). However, as Bratzel (2009) points out, this challenge can be extended beyond this particular set of big ideas to include an encompassing big idea: conservation. A focus on the conservation of energy takes this challenge to a higher level by mediating the exploration about *why* you have to make a trade-off between speed and torque.

Content encompassing big ideas usually are based around a theme that enables interdisciplinary lenses from science, technology, engineering, and mathematics to be brought to bear on important problems (Johnson, Peters-Burton, & Moore, 2016; Mayes & Myers, 2014). The major motivation behind the use of these themes is to improve student engagement in STEM by: (a) situating the study of STEM in contexts that are familiar and relevant to the students, and (b) studying global challenges addressed by STEM. For example, Mayes and Myers (2014) centered many of their integrated STEM curriculum units around "grand challenges". Grand challenges (e.g., how human activity is perturbing the six nutrient cycles of carbon, oxygen, hydrogen, nitrogen, sulfur, and phosphorus) are authentic real-world problems identified by experts as being challenges for the next generation (National Academy Press, 2001). Mayes and Myers argued that relating a STEM curriculum unit to grand challenges facing humanity "gives the curriculum unit immediate legitimacy in the eyes of both teachers and students" (2014, p. 75). In a similar vein, Johnson, Peters-Burton, and Moore (2016) centered their integrated STEM curriculum units around five themes that related the learning of STEM both to the students’ real world and to global challenges: (a) cause and effect, (b) innovation and progress, (c) the represented world, (d) sustainable systems, and (e) optimizing the human experience.

Designing Integrated Curriculum Units with STEM Big Ideas in Mind

The process of developing integrated STEM curriculum units based around big ideas is not a simple task (Cooper, 2014; English, 2016). To address this dilemma, the Robotics@QUT program (Chalmers, Wightman, & Nason, 2014) has developed a six-component framework to scaffold pre- and in-service teachers’ development of integrated STEM curriculum units based around big ideas. Although the components are listed below in a linear fashion, developing integrative STEM units is not a linear process—instead it is an iterative process (Vasquez et al., 2013). Thus, the framework should be applied in an iterative rather than a linear manner.

Select Big Ideas

Many STEM big ideas can be directly sourced from STEM discipline curriculum documents (e.g., Australian Curriculum, Assessment and Reporting Authority, 2013a, 2013b, 2013c; Ministry of Education, 2006), frameworks (e.g., National Research Council, 2011), standards (e.g., Harlen, 2010; NGSS Lead States, 2013), and textbooks (e.g., Small, 2009). Vasquez et al. (2013) used this process to identify connections among the STEM practices (see Figure 5.2 in Vasquez et al., 2013, p. 38); they identified modeling as a big idea that transcends science, engineering, and mathematics. However, this is not always possible because of the different ways the curriculum documents, frameworks, standards documents, and textbooks from the different STEM disciplines are structured. In this case, a strategy using an inductive methodology (similar to that used in grounded theory-based research) can be used to cumulate STEM big ideas suitable for use in integrated STEM curriculum units from these sources. Chalmers and Nason (in press), Rusk, Resnick, Berg, and Pezalla-

Granlund (2008), and Silk et al. (2010) suggested that the focus of a curriculum unit should be on a relatively few targeted big ideas and the connections between them during the course of the unit, whilst temporarily pushing other concepts into the background.

Look Closely at the Big Ideas

After the targeted STEM big ideas for an integrated curriculum unit have been selected, unit developers then have to consider how big ideas can be implemented to foster deep learning of knowledge of and about STEM. During these considerations, unit developers need to concurrently focus on two types of knowledge associated with each targeted big idea: (a) component understandings (Charles, 2005; Cooper 2014; Hurst & Hurrell, 2014; Siemon et al., 2012) and (b) horizon knowledge (Ball, Thames, & Phelps, 2008; Cooper, 2014). Each STEM big idea is underpinned by a system of component understandings (Charles, 2005; Cooper 2014; Hurst & Hurrell, 2014; Siemon et al., 2012). Therefore, once a big idea of and/or about STEM has been targeted for foregrounding in an integrated curriculum unit, the system of component understandings underpinning the big idea should be identified and defined. This process can often be achieved by a close analysis of STEM curriculum and standards documents.

The learning of big ideas needs to be conceptualized as something that occurs over a period of time and in a number of different contexts (Cooper & Warren, 2011; Harlen, 2010). Therefore, it is essential that teachers not only know what prerequisite knowledge and understandings are necessary for learning a targeted big idea but also know how the big idea they are currently teaching is related to the mathematical topics their students could encounter in the future. Ball et al. (2008) refer to this latter type of teacher content knowledge as "horizon knowledge".

Decide on a Topic for the Integrated Unit

One of the central tenets of STEM education is that students should be given opportunities to apply science, technology, engineering, and mathematics in contexts that not only better reflect the multidisciplinary and interdisciplinary nature of the work of most current STEM professionals (Lantz, 2009; Wang et al., 2011) but also make connections between school, community, and work (Tsupros et al., 2009). Therefore, in addition to being the “hook” that engages students in the curriculum unit (Clayton, 2010), the topic for an integrated STEM curriculum unit based on STEM big ideas should have the following characteristics: (a) it should connect the targeted STEM big idea(s) to real-world challenges, (b) it should be relevant to students’ lives and interests, and (c) it should be general enough to include two or more of the STEM disciplines (Clayton, 2010; Moore et al., 2014; Vasquez et al., 2013).

Select Thinking Tools

Thinking tools have important roles in supporting the learning of big ideas of and about STEM during the course of integrated STEM curriculum units (Kokotovich, 2008; Puntambekar & Kolodner, 2005). Therefore, decisions about what thinking tools can be used and how they should be used during the course of a curriculum unit need much thought. Chalmers and Nason (in press) identified three types of thinking tools that can be used to facilitate in-depth learning of STEM big ideas during the course of integrated STEM curriculum units: (a) external representation generating tools (e.g., concept maps, flow charts, tables and graphs, construction diagrams/plans); (b) tools for looking at problems from different perspectives (e.g., improvement triggers [Eberle, 1997], six thinking hats [de Bono, 1985], memos to clients [Lesh & Clarke, 2000]); and (c) reflection tools. External representation tools facilitate the construction of external representations that help learners to collect, organize, absorb and understand information, and advance knowledge (Caviglioli, Harris, & Tindall, 2002). Thinking tools that enable students to look at problems from different perspectives help them to break free from unproductive mindsets (e.g., focusing on trial-and-error strategies during the design of robots) and/or to overcome impasses (e.g., finding that the robot they are creating does not work as well as expected). Reflection tools have important roles in promoting reflection about task- and team-work before, during and after the completion of a project/challenge/task (Chalmers, 2009; Hamilton, Lesh, Lester, & Brilleslyper, 2008). Reflection tools help students recall and then record significant aspects about what they have done and thus enable students to: (a) relate new knowledge to their prior understanding, (b) mindfully abstract knowledge, and (c) understand how their learning and problem-solving strategies might be reapplied (Hmelo-Silver, 2004).

Design Assessment

Because assessment sends a clear message to students about what is worth learning, how it should be learned, and how well we expect them to perform (Educational Testing Service, 2003), it is imperative that assessment be philosophically consistent with the pedagogical framework implicit in the integrated STEM curriculum units (Chalmers & Nason, in press; Clayton, 2010). Chalmers and Nason (in press) identified four types of assessment tools that could be used in integrated STEM curriculum units: (a) collections of students’ work selected to document progress within a given challenge/project/task (e.g., portfolios, engineering design notebooks, robotic design journals); (b) tools that provide opportunities for students to demonstrate prototypes, describe their design solution and process, and describe the rationale for arriving at their solution (e.g., presentations, demonstrations, reports/memos, poster sessions, video journals, exhibitions); (c) external representations of students’ understanding of STEM concepts and processes (e.g., concept maps, flow charts, tables and graphs, construction diagrams/plans); and (d) tools to identify students’ understanding of STEM concepts/ processes (e.g., observations, interviews, examination, reflective essay). Many of these tools can be used for formative, diagnostic, or summative assessment. Clayton (2010) and Vasquez et al. (2013) both suggested that when working on the development of assessment for an integrated STEM curriculum unit, it is valuable to work backwards; begin thinking about the summative culminating event and then design the formative student work products that demonstrate students’ learning and help them prepare for it.

Design the Learning Activities

One lesson by itself will not build in-depth understanding of targeted big ideas (Chambers, Carbonaro, & Murray, 2008; Krajcik, Codere, Dahsah, Bayer, & Mun, 2014; Silk, 2011). Sequences of structurally related STEM learning activities conducted over a number of class periods, in conjunction with discussions and explorations focusing on structural similarities among the related activities, are needed (Krajcik et al., 2014; Lesh, Cramer, Doerr, Post, & Zawojewski, 2003). Therefore, in the framework for an integrated STEM curriculum unit we include four different types of learning activities: (a) preliminary activity, (b) core integrated STEM activity, (c) big ideas exploration activities, and (d) synthesizing activity.

Preliminary activity. The primary goal of the preliminary activity is to introduce the topic of the integrated curriculum unit to the students and familiarize them with the context of the STEM challenge/project/task that forms the core of the integrated STEM curriculum unit. Lesh and Doerr (2003) and Moore et al. (2014) suggested that familiarizing students with the context of a challenge/project/task can be achieved by providing students with background information via short articles, webpages, and video clips accompanied by questions that: (a) help ensure that the solutions to the STEM challenge/project/task are based on extensions of students’ real-life knowledge and experiences; and (b) answer teachers’ questions about “minimum prerequisites” for students to begin working on the challenge/project/task (Lesh & Doerr, 2003; Silk, 2011).

Core integrated STEM activity. In this activity, teams of students engage in a challenge/project/task that can only be completed when relevant STEM big ideas from more than one STEM discipline are applied. These activities typically require at least two or three full class periods (Hynes & Tada, 2008; Moore et al., 2014). At the end of each class period during the course of this core activity, the knowledge-building aspects of the activity can be further enhanced by the use of pin-up sessions, presentations and discussions, and reflection and debriefing activities. In pin-up sessions, students periodically present their ideas and sketches by creating a poster, pinning it to the wall, and then explaining to the class their intentions and how they plan to achieve them (Puntambekar & Kolodner, 2005). Presentations and discussions are whole-class activities in which students make formal presentations about what they have created and how they created it. The primary goals here are for students to explain their work, see other students’ alternative approaches and outcomes, discuss strengths and weaknesses, and identify directions for improvement for their own work and the work of others. The primary goal of reflection and debriefing activities is to help students assume a reflective and strategic stance towards learning (Darling-Hammond, Austin, Cheung, & Martin, 2008) and adopt an “increasingly productive personae for learning and problem solving” (Lesh & Doerr, 2003, p. 50).

Big ideas exploration activities. According to Lesh and Doerr (2003), to help students go beyond thinking *with* a big idea to also thinking *about* it, several structurally similar embodiments are needed. That is, students need to focus on similarities and differences as the big idea(s) function in different embodiments. Thus, the primary goal here is to form a cognitive link between embodiments of the big idea(s) foregrounded in the challenge/project/task and other more STEM discipline-specific embodiments of the big ideas. During these activities, students need to investigate structure-related relationships among several alternative embodiments—perhaps by making translations or predictions from one embodiment to another. Big ideas exploration activities should be conducted within science, technology, and/or mathematics classes during and especially after the core integrated STEM activity.

Synthesizing activity. The primary goal here is to provide closure and have students go beyond thinking with the targeted big idea(s) and advance towards making the big idea(s) explicit knowledge objects of thought that serve in the further advancement of knowledge. Knowledge-building (e.g., Bereiter & Scardamalia, 2010) and Model-Eliciting Activities (MEAs) research (e.g., Lesh & Doerr 2003; Moore et al., 2014) indicates that this process can be facilitated by whole-class teacher-led activities that focus on structural similarities and differences between the different embodiments of the big idea(s) explored during the course of the integrated STEM curriculum unit.

An Illustrated Example of the Framework in Action

We will look at an example to illustrate this framework for scaffolding the design of integrated STEM curriculum units in action. The example we have chosen is an integrated STEM unit centered on a middle school robotics design activity. Whilst reading the following text, one may be given the impression that a linear sequence of six steps was used to generate the integrated STEM curriculum unit centered on the design of a robot. However, this is far from the truth. Instead, it was an iterative process in which much backtracking and revisions were made to various components in the design framework. For example, after work was done on the design of the assessments, major revisions were made to the plans for the learning activities and the thinking tools.

Step 1: Select the Topic

In this example, the topic of the unit is: *Design of a multi-terrain rescue vehicle*. This topic has its genesis in a recent television news story that reported on the problems faced by a rescue service in a third-world Asian nation engaged in the process of rescuing an Australian tourist critically injured in mountainous jungle terrain. The report claimed that because the rescuers lacked an adequate multi-terrain rescue vehicle capable of traversing up narrow mountainous tracks, the tourist had to be taken out of the mountainous terrain by foot; because of the long time taken to extricate the tourist, she died. In addition to providing a “hook” to engage students in the integrated STEM curriculum unit, this topic was selected because we felt that it would provide a rich real-world context for the exploration of big ideas from more than one STEM discipline.

Step 2: Select Big Ideas

After selecting the topic for the integrated unit, the following list of targeted STEM big ideas was generated from an analysis of robotics and STEM curriculum documents (e.g., Hynes & Tada, 2008), websites (e.g., Chalmers & Rankin, n.d.; Carnegie Mellon Robotics Academy, 2013), texts (Bratzel, 2009), and journal articles (e.g., Chambers et al., 2008; Wendell & Rogers, 2013): *gears, speed* and *torque* (science), *ratios* (mathematics), and *EDP* and *trade-offs* (technology/engineering). Based on the work of Bratzel (2009), it is envisaged that using these big ideas should enable the students to progress beyond trial-and-error design strategies during the course of systematically and iteratively planning, prototyping, evaluating, and refining the design of the rescue vehicle.

Step 3: Look Closely at Targeted Big Ideas

During this step, we first unpacked each of the targeted big ideas in order to identify their component understandings. Two very important component understandings for gears identified as having much relevance for this unit were: (a) If in a gear train the first (Drive) gear has fewer teeth and the second (Driven) gear has more teeth, the result will be reduced speed but more torque; and (b) If in a gear train the first (Drive) gear has more teeth and the second (Driven) gear has fewer teeth, the result will be increased speed but less torque. The component understandings unpacked from the mathematics big idea of ratios was that ratios are ordered pairs (i.e., the ratio of 2:3 is not equivalent to 3:2). Thus, a gear train with a ratio of 2:1 between the number of teeth on the first and second gear will not produce the same outcome in terms of speed and torque as a gear train with a ratio of 1:2. The component understanding unpacked from EDP was that engineering design is systematic and iterative; thus EDP should not be perceived as a list of sequenced steps but as a conceptual framework for systematic and iterative design.

Second, we identified horizon knowledge (Ball et al., 2008) for the targeted big ideas. In particular, we identified how ratios could be extended beyond the context of gears, speed, and torque to other contexts where ratios were used (e.g., ratios and slopes in mathematics courses, ratios and mixtures in science courses). The encompassing big idea of conservation of energy was identified as the means to explore why a trade-off between speed and torque often is necessary when selecting gears for a gear train.

Step 4: Design Learning Activities

Preliminary activity. In order to provide a meaningful context for the robotics design task, we decided to begin with an edited version of the television news story followed up by a worksheet in which the students are presented with the problem statement for the robotics design task. In the problem statement, students are presented with a scenario in which a rescue service “client’ discusses his service’s need for a new rescue vehicle that can: (a) transport two patients and two paramedics, (b) climb up very steep mountainous jungle tracks, and (c) also move quickly once it has reached flatter terrain in the valleys. The students are told that the head of the rescue service (their client) has commissioned them to design a multi-terrain rescue vehicle that addresses these three criteria. To conclude the preliminary activity, the students are presented with the following set of readiness questions: (a) Why does the rescue service need a new type of rescue vehicle? (b) What must the new rescue vehicle be able to do? (c) What previous STEM knowledge could we use to construct the rescue vehicle? and (d) How could we judge which is the best design for the client?

Core integrated STEM activity. In this activity, teams of three or four students work on the design of the rescue vehicle over a period of three to four one-hour sessions. In session 1, the teams plan and design a prototype. In session 2, the teams evaluate and modify their prototype. In session 3, the teams further develop and then present their final design to the “client”. During the whole course of this activity, the teams are required to record in a design journal what they did, what they modified, and what they learned. At the end of lessons 1 and 2, the teams first are required to write interim memos to the client describing: (a) what they have done, (b) what changes they have made to their design, (c) what they have learned, and (d) what they plan to do in the next session. This prepares the teams to make a brief report/presentation/ demonstration to the whole class. During these whole-class sessions, the effectiveness of the different designs in meeting the needs of the client is discussed. At the end of the final lesson, each team presents their final product and report to the client. During the course of the three lessons, teachers are expected to continually foreground each of the targeted STEM big ideas (c.f., Chalmers & Nason, in press; English, 2016; Silk et al. 2010) and make the connections to the STEM big ideas apparent to the students (c.f., English, 2016; Johnson et al., 2016; Moore et al., 2014).

Big ideas exploration activities. For these activities, we identified different embodiments of the big ideas targeted in the core integrated STEM activity that can be explored during the course of science, technology/engineering and mathematics lessons. Thus, it was envisaged that the targeted big idea of ratios could be explored in the contexts of: (a) chemical mixtures (in science lessons); (b) scale drawings (in technology/engineering lessons); and (c) slopes and geometrical shapes (in mathematics lessons). In these lessons, the structural similarities and differences between the different embodiments of ratios in science, technology/

engineering, and mathematics could be explored (c.f., Cooper, 2014; Harlen, 2010; Moore et al., 2014; Puntambekar & Kolodner, 2005). It was also envisaged that mathematical embodiments of the technology/engineering big idea of trade-off could be explored during the course of mathematics lessons (e.g., 99 + 14 = 100 + ☐, where if 1 is added to the 99, then 1 has to be subtracted from the 14 to keep the total the same; inverse relationships).

Synthesizing activity. We focused this whole-class activity around three questions: (a) What did you do during the course of this curriculum unit? (b) What do you think you learned from this curriculum unit? and (b) What questions do you have as a result of completing this unit?

Step 5: Select Thinking Tools

In order to facilitate in-depth exploration of the targeted big ideas during the course of the unit, the following thinking tools were selected: (a) external representation tools—concept maps, tables and graphs, models, diagrams and plans; (b) different perspective tools—memos to client; and (c) reflection tools—task reflection questionnaire.

Step 6: Design Assessment

The following assessment tools were selected: (a) design journal, (b) memos to clients, (c) demonstrations of rescue vehicles, (d) final report and demonstration to client, and (e) summative test. Assessment tools (a) to (c) were selected because they could be used for formative, diagnostic, and summative assessment. It is envisaged that the use of assessment tools (a) to (c) would scaffold the systematic and iterative use of the engineering design process during the process of planning and designing the multi-terrain rescue vehicle. Assessment tools (d) and (e) were selected for summative assessment.

Conclusion

In this paper, we presented a six-component framework based on a continuum of STEM big ideas for scaffolding the design of integrated STEM curriculum units that facilitate in-depth learning of and about STEM. We conjecture that examining an issue from a cross-discipline perspective and/or from various perspectives of the STEM discipline, such as that envisaged by the approach proposed in this paper, encourages the mental connections that enhance understanding of and about STEM. It requires students to learn both the shared language of STEM and the different words used for the same concept in other branches of STEM (e.g., what a mathematician calls “gradient” might be called “pitch” by an engineer and “steepness” by a scientist). It also enhances not only width but depth of knowledge. For example, using the different ways that the various STEM disciplines represent their ideas (e.g., trade-offs in engineering might be presented as a graph in science and an inverse relationship in mathematics) not only mediates width of knowledge across STEM but also depth of knowledge within the STEM disciplines.

Many schools face practical difficulties in integrating the STEM disciplines; for example, timetabling, teacher skills, differing curriculum demands and assessment criteria, and the fact that in some school systems and/or year levels some of the STEM disciplines are optional. Lack of expertise in each area also can be problematic for implementation. Different teachers have more in-depth knowledge in each field. For example, many elementary school teachers have limited repertoires of subject-matter knowledge in engineering, technology, and many of the sciences. In middle and high schools, biology teachers have different knowledge than physics teachers, which is different than that of mathematics teachers.

Based on our work-in-progress experiences with STEM big ideas in the YuMi Deadly Maths (Cooper, 2014) and the Robotics@QUT (Chalmers, Wightman, B., & Nason, 2014) programs, we believe that our six-component big ideas framework can provide STEM education with the means to address many of these problems. For example, many of the elementary school teachers in the YuMi Deadly Maths program schools perceived that they had inadequate repertoires of mathematical content and pedagogical knowledge and this was limiting their ability to meet the mathematics education needs of their indigenous and/or low-SES students. The principals and curriculum coordinators in many of the elementary schools involved in this program have informally reported back to the YuMI Deadly Maths team that they feel that having teachers base their math curriculum planning around a few mathematics big ideas has helped the teachers to become more confident and competent teachers of mathematics. These impressions have been backed up by improved performance by their students in the National Assessment Program Language and Mathematics [NAPLAN] Year 5 mathematics tests (Australian Curriculum, Assessment, and Reporting Authority, 2016).

As was noted in the introduction of this paper, the six-component framework should be perceived as being a “work-in-progress”. For example, we have not as yet conducted systematic evaluations of the framework to determine if its effective use by elementary, middle, or high school teachers necessarily leads to the design of integrated STEM curriculum units that mediate in-depth knowledge of and about STEM. Also, we have as yet not fully investigated other important issues such as: (a) How can the framework be used to overcome impediments to the application of integrated STEM curriculum caused by the testing regimes in many countries? (b) What are the pre- and in-service teacher education implications of the framework? and (c) How can research based around the framework be conceptually related to research on learning trajectories (e.g., Wilson, Mojica, & Confrey, 2013)? If issues such as these could be addressed in future research and development, this would do much to advance the design and implementation of integrated STEM curriculum units in particular and STEM education in general.

References

Askew, M. (2013). Big ideas in primary mathematics: Issues and directions. *Perspectives in Education, 31*(3), 5-18.

Australian Curriculum, Assessment and Reporting Authority. (2013a). *The Australian Curriculum: Mathematics.* Retrieved from http://www.australiancurriculum.edu.au/Australian%20Curriculum.pdf

Australian Curriculum, Assessment and Reporting Authority. (2013b). *The Australian Curriculum: Science.* Retrieved from http://www.australiancurriculum.edu.au/Australian%20Curriculum.pdf

Australian Curriculum, Assessment and Reporting Authority. (2013c). *The Australian Curriculum: Technologies Foundation to Year 10.* Retrieved from http://www.australiancurriculum.edu.au/Australian%20Curriculum.pdf

Australian Curriculum, Assessment and Reporting Authority. (2016). *National Assessment Program Language and Mathematics* Retrieved from http://www.nap.edu.au

Ball, D. L., Thames, M. H., & Phelps, G. (2008). Content knowledge for teaching: What makes it special? *Journal of Teacher Education, 59*(5), 359-407.

Bereiter, C., & Scardamalia, M. (2010). Can children really create knowledge? *Canadian Journal of Learning and Technology, 36*(1), 1-15. Retrieved from http://www.cjlt.ca/index.php/cjlt/article/view/585/289

Berland, L. K. (2013). Designing for STEM integration. *Journal of Pre-College Engineering Education Research (J-PEER*), *3*(1), 22-31. http://dx.doi.org/10.7771/2157-9288.1078

Bratzel, B. (2009). *Physics by design with NXT Mindstorms* (3rd ed.). Knoxville, TN: College House Enterprises.

Brooks, M. G., & Grennon Brooks, J. (1999). The courage to be constructivist. *The Constructivist Classroom, 57*(3), 18-24.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher, 18*, 32-42.

Bruner, J. S. (1960). *Toward a theory of instruction*. Harvard University Press.

Carnegie Mellon Robotics Academy. (2013). *Robot Algebra Project*. Retrieved from http://www.education.rec.ri.cmu.edu/content/educators/research/robot_algebra/index.htm

Caviglioli, O., Harris, I., & Tindall, B. (2002). *Thinking skills and Eye Q: Visual tools for raising intelligence*. Stafford: Network Educational Press Ltd.

Chalmers (2009). *Primary students' group metacognitive processes in a computer supported collaborative learning environment* (PhD thesis, Queensland University of Technology). Retrieved from http://eprints.qut.edu.au/29819/

Chalmers, & Rankin, C. (n.d.). Curriculum. Sydney, Australia: LEGO Education. Retrieved from https://education.lego.com/en-au/curriculum

Chalmers, C., Wightman, B., & Nason, R. (2014). *Engaging students (and their teachers) in STEM through robotics.* In STEM 2014 Conference, July 12–15, 2014, Vancouver, Canada. Retrieved from http://eprints.qut.edu.au/84571

Chalmers, C., & Nason, R. (in press). In M. S. Khine (Ed.). *Robotics in STEM education: Redesigning the learning experience.*

Chambers, J. M., Carbonaro, M., & Murray, H. (2008). Developing conceptual understanding of mechanical advantage through the use of Lego robotic technology. *Australasian Journal of Educational Technology, 24*(4), 387-401.

Charles, R. I. (2005). Big ideas and understandings as the foundation for elementary and middle school mathematics. *Journal of Mathematics Education Leadership*, 7(3), 9-24.

Chi, M. T. H., Glaser, R., & Farr, M. J. (1988). *The nature of expertise.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Clayton, M. (2010). *Designing multidisciplinary integrated curriculum units.* Berkeley, CA: ConnectEd The California Center for College and Career.

Cooper, T. (2014). *YuMi Deadly Maths: Big ideas for mathematics: Prep to Year 9.* Kelvin Grove, Qld: YuMi Deadly Centre, Queensland University of Technology.

Cooper, T.J., & Warren, E. (2011) Years 2 to 6 students' ability to generalise : models, representations and theory for teaching and learning. In J. Cai, & E. Knuth (Eds.) *Early Algebraization* (pp. 187-214). Berlin Heidelberg: Springer-Verlag.

Cuoco, A., Goldenberg, E. P., & Mark, J. (2010). Contemporary curriculum issues: Organizing a curriculum around mathematical habits of mind. *Mathematics Teacher, 103*(9), 682-688.

Czerniak, C. M., & Johnson, C. C. (2014). Interdisciplinary science and STEM teaching. In N. G. Lederman & S. K. Abell, (Eds.), *Handbook of Research on Science Education* (2nd ed., pp. 395-412). Mahwah, NJ: Lawrence Erlbaum Associates.

Darling-Hammond, L., Austin, K., Cheung, M., & Martin, D. (2008). Session 9: Thinking about thinking – Metacognition. In *The Learning Classroom: Theory into Practice* (pp. 157-172). Stanford University School of Education. Retrieved from http://www.learner.org/courses/learningclassroom/

Daugherty, J. (2012). Infusing engineering concepts: Teaching engineering design. *National Center for Engineering and Technology Education*. Retrieved from http://files.eric.ed.gov/fulltext/ED537384.pdf

de Bono, E. (1985). *Six Thinking Hats: An essential approach to business management*. New York: Little, Brown and Co.

Eberle, B. (1997). Scamper worksheet. Retrieved from http://bmgi.org/toolstemplates/scamper-worksheet

Education Council. (2015). *National STEM school education strategy 2016–2026*. Retrieved from www.educationcouncil.edu.au

Educational Testing Service. (2003). *Linking classroom assessment with student learning.* Princeton, NJ: Educational Testing Service. Retrieved from https://www.ets.org/Media/Tests/TOEFL_Institutional_Testing.../ELLM2002.pdf

English, L. D. (2016). STEM education K–12: Perspectives on integration. *International Journal of STEM Education, 3*(3), 1-8. doi10.1186/s40594-016-0036-1

Fortus, D., Krajcik, J., Dershimer, R. C., Marx, R. W., & Mamlok-Naaman, R. (2005). Design-based science and real-world problem-solving. *International Journal of Science Education, 27*(7), 855-879.

Fosnot, C. T. (2007). Our teaching and learning philosophy. In C. T. Fosnot (Ed.), *Investigating multiplication and division Grade 3–5* (pp. 13-15). Portsmouth, NH: Heinemann.

Glaser, R. (1983). *Education and thinking: The role of knowledge* (Technical Report No. PDS-6). Learning Research and Development Center, University of Pittsburgh.

Gomez-Zweip, S. (2016). Science, technology, engineering and math (STEM) curricula in the US and other contexts. In D. Wyse, L. Hayward, & J. Pandya (Eds.), *The Sage handbook of curriculum, pedagogy and assessment* (pp. 655-672). London: Sage Publications.

Grennon Brooks, J., & Brooks, M. G. (1993). *In search of understanding: The case for constructivist classrooms.* Alexandria, VA: ASCD.

Gurung, N., & Hayne, A. (2009). *Exploring signature pedagogies: Approaches to teaching disciplinary habits of mind*. Sterling, VA: Stylus Publishing.

Hamilton, E., Lesh, R. Lester, F. & Brilleslyper. M. (2008). Model-Eliciting Activities (MEAs) as a bridge between engineering education research and mathematics education research. *Advances in Engineering Education, 1*(2), 1-25.

Harlen, W. (Ed.). (2010). *Principles and big ideas of science education.* Hatfield, UK: Association of Science Teachers.

Hefty, L. J. (2015). Applying mathematics during engineering design challenges can help children develop critical thinking, problem solving, and communication skills. *Teaching Children Mathematics*, *21*(7), 423-429.

Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review, 16*(3), 235-266.

Honey, M., Pearson, G., & Schweingruber, A. (2014). *STEM integration in K–12 education: status, prospects, and an agenda for research*. Washington, DC: National Academies Press.

Hurst, C. (2015). Thinking big about mathematics, science, and technology: Effective teaching STEMs from big ideas. *International Journal of Innovation in Science and Mathematics Education, 23*(3), 11-21.

Hurst, C., & Hurrell, D. (2014). Developing the big ideas of number. *International Journal of Educational Studies in Mathematics, 1*(2), 1-18.

Hynes, M., & Tada, H. (2008). *Robotics: Assistive design for the future.* Boston, MA: Tufts Center for Engineering Educational Outreach and LEGO engineering.com. Retrieved from http://www.legoengineering.com/wpcontent/uploads/2013/05/LEcom_AssistiveTechRobotics.pdf

Johnson, C. C., Peters-Burton, E. E., & Moore, T. J. (Eds.). (2016). *STEM road map: A framework for integrated STEM education*. New York, NY: Routledge.

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education, 3*(11). doi10.1186/s40594-016-0046-z

Khishfe, R., & Lederman, N. (2006). Teaching nature of science within a controversial topic: Integrated versus nonintegrated. *Journal for Research in Science Teaching, 43*(4), 395-418.

King, J. (2014). *STEM and the Australian Curriculum.* Canberra, ACT: Australian Curriculum, Assessment and Reporting Authority.

Kokotovich, V. (2008). Problem analysis and thinking tools: an empirical study of non-hierarchical mind mapping. *Design Studies, 29*(1), 49-69.

Krajcik, J., Codere, S., Dahsah, C., Bayer, R., & Mun, K. (2014). Planning instruction to meet the intent of the Next Generation Science Standards. *Journal of Science Teacher Education, 25*(2), 157-175.

Lantz, H. B. (2009). *What is STEM education?* Retrieved from http://www.currtechintegrations.com/pdf/STEMEducationArticle.pdf

Lave, J., & Wenger, E. (1991). *Situated learning. Legitimate peripheral participation*. Cambridge University Press.

Lesh, R., & Clarke, D. (2000). Formulating operational definitions of desired outcomes of instruction in mathematics and science education. In A. E. Kelly & R. A. Lesh (Eds.), *Handbook of research design in mathematics and science education* (pp. 113-149). Mahwah, NJ: Lawrence Erlbaum.

Lesh, R., Cramer, K., Doerr, H., Post, T., & Zawojewski, J. S. (2003). Model development sequences. In R. Lesh & H. Doerr (Eds.), *Beyond constructivism: Models and modeling perspectives on mathematics problem solving, learning, and teaching* (pp. 35-54). Mahwah, NJ: Lawrence Erlbaum Associates.

Lesh, R. & Doerr, H. M. (Eds.). (2003). *Beyond Constructivism*. Mahwah, NJ: Lawrence Erlbaum Associates.

Marshall, S. P. (2010). Re-imaging specialized STEM academies: Igniting and nurturing decidedly different minds by design. *Roeper Review, 32*(1), 48-690.

Mayes, R., & Myers, J. (2014). *Quantitative reasoning in the context of energy and environment: Modeling problems in the real world*. Boston, MA: Sense Publishers.

Metz, S. (2012). Big ideas. *The Science Teacher, 79*(5), 6.

Michaels, S., Shouse, A. W., & Schweingruber, H. A. (2007). *Putting research to work in K–8 science classrooms.* Washington, DC: The National Academies Press.

Ministry of Education. (2006). *A guide to effective instruction in mathematics, Kindergarten to Grade 6: Number sense and numeration, Grades 4 to 6, Vol. 1: The big ideas*. Toronto, ON: Queen’s Printer for Ontario.

Moore, T. J., Stohlmann, M. S., Wang, H.-H., Tank, K. M., Glancy, A. W., & Roehrig, G. H. (2014). Implementation and integration of engineering in K–12 STEM education. In S. Purzer, J. Strobel, & M. Cardella (Eds.), *Engineering in precollege settings: Research into practice* (pp. 35-60). West Lafayette, IN: Purdue Press.

National Academy of Engineering. (2014). *STEM integration in K–12 education: Status, prospects, and an agenda for research.* Retrieved from http://www.nap.edu/stem-integration

National Academy Press. (2001). Grand challenges in environmental sciences. Retrieved from https://www.nap.edu/read/9975

National Research Council. (2011). *A framework for K–12 science education: Practices, crosscutting concepts, and core ideas.* Washington, DC: The National Academy Press.

Next Generation Science Standards Lead States. (2013). *Next generation science standards: For states by states.* Washington, DC: The National Academies Press.

Niemi, D., Vallone, J., & Vendlinski, T. (2006). *The power of big ideas in mathematics education: Development and pilot testing of POWERSOURCE assessments* (CSE Report 697). Los Angeles, CA: National Center for Research on Evaluation, Standards, and Student Testing (CRESST), University of California.

Palincsar, A. S. (1998). Social constructivist perspectives on teaching and learning. *Annual Review of Psychology, 49*, 345-375.

Piaget, J. (1977). *Epistemology and psychology of functions*. Dordrecht, Netherlands: D. Reidel Publishing Company.

Piaget, J. (1985). *The equilibration of cognitive structures. The central problems of intellectual development*. Chicago, IL: University of Chicago Press.

Pruett, S. (2015). *Don't leave math (or math teachers) at the STEM starting gate*. Retrieved from www.middleweb.com/22173/stem-programs-must-not-leave-math-behind/

Puntambekar, S., & Kolodner, J. L. (2005). Distributed scaffolding: Helping students learn science by design. *Journal of Research in Science Teaching, 42*(2) 185-217.

Richland, L. E., Stigler, J. W., & Holyoak, K. J. (2012). Teaching the conceptual structure of mathematics. *Educational Psychologist, 47*(3), 189-203. doi:10.1080/00461520.2012.667065

Rusk, N., Resnick, M., Berg, R., & Pezalla-Granlund M. (2008). New pathways into robotics: strategies for broadening participation. *Journal of Science Education and Technology, 17*(1), 59–69.

Schifter, D., & Fosnot, C. T. (1993). *Reconstructing mathematics education*. New York: Teachers College Press.

Schoenfeld, A. H. (2016). Solving the problem of powerful instruction. In C. Csíkos, A. Rausch, & J. Szitányi, (Eds.), *Proceedings of the 40th Conference of the International Group for the Psychology of Mathematics Education, Vol. 1* (pp. 3-18). Szeged, Hungary: PME.

Siekmann, G. (2016). *What is STEM? The need for unpacking its definitions and applications*. Adelaide, SA: National Centre for Vocational Education Research.

Siemon, D., Bleckly, J., & Neal, D. (2012). Working with the big ideas in number and the Australian Curriculum: Mathematics. In B. Atweh, M. Goos, R. Jorgensen, & D. Siemon (Eds.), *Engaging the Australian National Curriculum: Mathematics—Perspectives from the field* (pp. 19-45). Mathematics Education Research Group of Australasia.

Silk, E. M. (2011). *Resources for learning robots: Environments and framings connecting math in robotics* (Unpublished doctoral dissertation). University of Pittsburgh.

Silk, E. M., Higashi, R., Shoop, R., & Schunn, C. D. (2010). Designing technology activities that teach mathematics. *The Technology Teacher, 69*(4), 21-27.

Small, M. (2009). *Big ideas from Dr. Small, Grades 4–8.* Toronto, ON: Nelson Education Ltd.

Sneider, C. (2010). Appendix B: Draft—A vision of engineering standards in terms of big ideas. In Committee on Standards for K–12 Engineering Education, *Standards for K–12 Engineering Education?* (pp. 136-143). Washington, DC: The National Academies Press.

STEM-Ed Scotland. (2010). *General principles guiding a fresh approach to STEM education*. Retrieved from http://www.gla.ac.uk/colleges/scienceengineering/stemed/

Tsupros, N., Kohler, R., & Hallinen, J. (2009). *STEM education: A project to identify the missing components, Intermediate Unit 1.* Pittsburgh, PA: Carnegie Mellon University.

Vagla, V. M. (2016). Curriculum: Interdisciplinary unit. In S. B. Mertens, M. M. Caskey, & N. Flowers (Eds), *The encyclopedia of middle grades education 2nd edition* (pp. 122-125). Hershey, PA: Information Age Publishing.

Vasquez, J. A., Sneider, C., & Comer, M. (2013). *STEM lesson essentials: Integrating science, technology, engineering, and mathematics*. Portsmouth, NH: Heinemann.

Vygotsky, L. (1978). *Mind in Society*. London: Harvard University Press.

Wang, H., Moore, T. J., Roehrig, G. H., & Park, M. S. (2011). STEM integration: Teacher perceptions and practice. *Journal of Pre-College Engineering Education Research, 1*(2), 1-13.

Wendell, B. K., & Rogers, C. (2013). Engineering design-based science, science content performance, and science attitudes in elementary school. *Journal of Engineering Education, 102*(4), 513–540.

Wilson, P.H., Mojica, G.F., & Confrey, J. (2013). Learning trajectories in teacher education: Supporting teachers’ understanding of students’ mathematical thinking. *The Journal of Mathematical Behavior, 32*(1), 103-121.