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Title: Understanding K-12 STEM Education: A framework for developing STEM literacy

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Understanding K-12 STEM Education: A framework for developing STEM literacy

Abstract

In recent years, arguments have signalled the value of STEM education for building discipline knowledge and an array of capabilities, skills and dispositions, aligned with the needs of young people functioning productively and ethically in dynamic, complex and challenging future work, social and political environments. This combination has been termed *STEM literacy*, and positioned as a desired outcome from STEM education programs. However, knowledge is limited on ways this can be developed in K-12 schools. This article introduces a framework that conceptualises the integrated nature of the characteristics of STEM education. It identifies and maps key characteristics of STEM education, recognising different entry points, curriculum designs, and pedagogical strategies for school programs. The framework provides practical guidance for planning and implementing STEM education in schools.

Keywords. STEM, interdisciplinary, integrated, discipline, STEM literacy, School, K-12.

Introduction

Calls for enhanced STEM capability through improved STEM education, is a common theme in educational, economic and political discourse (e.g., Caprile, Palmen, Sanz & Dente, 2015; Marginson, Tytler, Freeman & Roberts, 2013). These calls frequently emanate from employers concerned about a lack of workplace-skilled professionals to fill current and emerging positions, particularly in innovation-based enterprises. Some point the finger at education, claiming, "the lack of employability is attributed to outdated curriculum and dearth of innovation (in schools)" (Marrero, Gunning & Germain-Williams, 2014, p.3). Others cite issues with many students' disinterest in science and technology, commenting that poor teaching and lack of relevance, has spawned negative attitudes that are difficult to dislodge (Bissaker, 2014; Newhouse, 2017; Roberts, 2012). Educationally, STEM is promoted as a means of addressing dwindling engagement through its focus on the integration of discipline knowledge to solve problems in authentic, 'real world' contexts (Honey, Pearson & Schweingruber, 2014). Integrated STEM education has been identified as a platform for developing important skills and competences, valuable both personally, and professionally. These include research inquiry, problem solving, critical and creative thinking, entrepreneurship, collaboration, teamwork and communication (English, 2016; Honey et al., 2014; Madden et al., 2013).

Furthermore, the potential of STEM education to engage community and businesses as contexts for and in supporting projects, enhances authenticity and purpose. STEM problem and project-based learning models also mirror processes often used in business and industry (Asghar, Ellington, Rice, Johnson & Prime, 2012; Breiner, Johnson, Harkness & Koehler, 2012; Portz, 2015). Design thinking skills frequently underpinning 'real world' product ideation and development are exercised through conceptualising, designing, prototyping and evaluating outcomes, artefacts and solutions. These skills, combined with what Hargrove (2011) describes as the cognitively-demanding nature of design processes within STEM endeavour, provide broad support for STEM education, supplementing economic and business arguments (Brears, MacIntyre & O'Sullivan, 2011). However, despite recognition of personal, societal and economic benefits from STEM education and its increasing inclusion in K-12 school curricula, different perspectives exist about how it should be planned, taught and assessed, that can cause confusion amongst those responsible for its implementation (Breiner et al., 2012; Honey et al., 2014; Newhouse, 2017).

What is STEM Education?

A singular, agreed to definition of STEM education is elusive, reflecting both the emergent nature of STEM as a ‘meta-discipline’, and debate relating to how separate STEM subjects are represented in K-12 STEM curricula. However, reasonable agreement exists that STEM education should have as a principal aim the development of Science, Technology, Engineering and Mathematics concepts, knowledge and process understandings, “through efforts to combine some of all of the four disciplines into one class, unit or lesson that is based on connections between subjects and real world problems” (Moore, Stohlmann, Wang, Tank, Glancy & Roehrig, 2014, p.38). While interdisciplinarity features prominently as an attribute of STEM education, different views exist about how STEM disciplines should be positioned and prioritised within interdisciplinary K-12 STEM curricula.

Statement of the Problem

While agreement exists about the *STEM literacy* goal of K-12 STEM education, just what this comprises and how it is achieved, is less clear. This challenges teachers who are expected to reconsider often strongly-held beliefs about teaching and learning located in individual STEM disciplines, to move towards multi or interdisciplinary approaches that involve solving problems or realising opportunities, located in ‘real world’ contexts. This challenge is compounded by the organisation and structure of schools, where separate departments often hold responsibility for curriculum aligned with individual disciplines. These structures promote a ‘silo’ effect where teachers plan and teach in isolation, delivering discipline content in what they see as the most efficient means possible, often to meet external assessment demands (Bybee, 2010; Newhouse, 2017; Zeidler, 2016; Zollman, 2012). Interdisciplinary STEM education challenges this approach, requiring more collaborative methods that combine multiple disciplines and different pedagogical skills.

This article introduces a framework that aims to guide teachers in planning and teaching STEM education. It was developed from a scoping review of literature that identified key concepts and characteristics of planning and teaching in STEM, and ways they are combined in STEM curriculum. The review firstly backgrounds different perspectives on STEM education, before explaining the concepts and characteristics. The characteristics are described in terms of their relevance to STEM curriculum and pedagogy, before illustrating via the framework, how they might integrate in different approaches to K-12 STEM education, focused on the common goal of building STEM literacy.

Review Method

An academic database search identified literature likely to provide insights into key concepts associated with K-12 STEM education. A scoping procedure was followed, as the method supports flexibility to investigate literature offering different perspectives on developing fields of teaching and research (Munn et al., 2018). While a definitive procedure for scoping reviews is yet to be defined (Anderson, Allen, Peckham & Goodwin, 2008; Arskey & O'Malley, 2005; Daudt, van Mossel & Scott, 2013), according to Munn et al. (2018) scoping reviews, "aim to provide an overview or map of the evidence… rather than a critically appraised and synthesised result or answer to a particular question" (p.3). They are suited to inquiries in developing areas where evidence is still emerging and perspectives vary, or as Munn states, "when it is still unclear what other, more specific questions can be posed and addressed by more systematic review" (p.2). According to Pham et al. (2014), scoping reviews follow a six-stage process, starting with a problem statement, sourcing relevant studies, study selection, presenting data, summarising results, and an optional consultation phase. Following an initial database scan using the keywords STEM AND education (OR school) the first author and a research assistant (the reviewers), identified four concepts as starting points likely to provide insights into understandings, focuses and approaches, to K-12 STEM education.

They were:

- knowledge (discipline), skills, competencies and capabilities;
- perspectives on, and approaches to, planning for STEM education;
- understandings of STEM curriculum and pedagogy;
- understandings of STEM literacy.

First, the review procedure involved identifying keywords aligned with the four STEM education concepts. Keywords were limited to those specific to school STEM literacy and planning, teaching and learning in school STEM, recognising the concept of STEM has relevance in other fields. Different combinations of keywords were entered into the database search, with Boolean operators used to define and emphasise important relationships between search terms (Appendix A). Filters were set to return English language full-access peer reviewed articles, reports, books and chapters, post 2007. The second stage involved refining results by identifying frequently published authors, specific to school STEM education. This comprised creating an author list from search results, before completing an advanced search by author, associated with the keywords "STEM education" (AND/OR school, curriculum, teaching) and "STEM literacy". This reduced the total publication count to 91.

The reviewers randomly divided the list and read the abstracts, methods and conclusions for each document. In the case of books, review comprised scanning the introduction and chapters of most relevance. Both reviewers used a template to complete summaries for each publication (Appendix B). After scanning the documents, the reviewers met and discussed results. Some authors were represented in multiple publications, however, often the focus of these publications was similar, so a decision was made to limit the number of publications for in-depth review from each author to three.

Interestingly, most publications were conceptual in nature (n=55), with fewer empirical studies (n= 24) and reports (n=12). While this possibly reflects the emergent nature of the field, it was important to include a balance of study types, corresponding approximately to the proportion of each represented in the sample. Using these criteria, the reviewers discussed the summaries and finalised a set of conceptual, empirical and report publications representative of the perspectives of authors. In total, 50 documents comprising 3 books, 7 chapters, 11 reports, 1 conference paper and 28 articles were selected for in-depth review.

Coding and Identification of Characteristics

The publications were divided between the reviewers and read closely, and authors' perspectives and understandings of characteristics aligned with the four concepts were identified, colour coded, and annotated. The reviewers shared, examined, and discussed each other's interpretations, before generating draft lists of characteristics aligned with the four concepts. To support validity, both reviewers blind checked a sample of each other's interpretations. This resulted in minor adjustments, and provided additional contextual information that was later used to create descriptive statements illustrative of how the characteristics were conceptualised. The finalised characteristics were then organised under ten themes, grouped according to common attributes. The original concept labels were adjusted, reflecting the overlap between curriculum and pedagogy and planning for STEM (merged), and the role of discipline knowledge (separated from capabilities, skills etc.). The final concepts and themes were:

STEM capabilities, skills and dispositions.

Themes: cognitive, creative thinking, personal capabilities, dispositions and attitudes;

STEM curriculum and pedagogy.

Themes: curriculum and learning design, pedagogy, working processes, design thinking;

STEM discipline knowledge.

Theme: disciplinarity – priority and positioning of discipline knowledge (orientation);

STEM Literacy.

Theme: the goal and purpose of STEM education.

A summary aligning the concepts, characteristics, themes and descriptors with authors, is provided in Appendix C.

Findings

This section presents the main findings, organised using the four concepts. First, context is provided by a discussion of the emergent nature of K-12 STEM education, as reflected in literature that indicated varying perspectives on what STEM education comprises, and how it should be planned, taught and assessed. This is necessary to position the analysis of characteristics in terms of the still-developing field, reflecting diverse views on the form and composition of STEM curriculum.

Different Perspectives on STEM Education

Bybee (2010) describes STEM education, "as a generic label for any event, policy, program or practice that involves one or several of the STEM disciplines" (p.30). However, literature suggests that understandings of the rationale for STEM education and its implications for teaching and learning are not well-understood, and vary according to the perspectives of different stakeholders (e.g., Breiner et al., 2012; Holmlund, Lesseig & Slavit, 2018; Honey et al., 2014; Newhouse, 2017; Sanders, 2012). For example, Techakosit and Nilsook (2018) comment that governments allocating billions of dollars to STEM in schools, generally do so with an expectation of long term economic value, by establishing a 'pipeline' producing work-ready employees, innovators and scientists, able to develop new, high value products and services. However, as Cockle (2018) and Zollman (2012) point out, teachers in classrooms charged with the responsibility of implementing STEM curriculum, struggle to grasp what STEM education 'looks like', how it should be planned, why and how they should revise historical teaching methods, and what and how student outcomes should be assessed and reported. Breiner et al. (2012) also suggest parents may question what they perceive as the 'non-conventional' pedagogies and curriculum associated with project-based STEM, possibly interpreting this as a 'dumbing down' of the academic rigor associated with traditional, discipline-based methods.

While there was tacit agreement that *a* driver for K-12 STEM education was addressing the pipeline challenge, some authors highlighted the danger of adopting a technocratic approach that results in 'siloed' teaching, focusing narrowly on technical outcomes (e.g., Asghar et al., 2012; Breiner et al, 2012; English, 2016; Salami, Makela & de

Miranda, 2017). These authors argued for a broader perspective – one that promotes positive personal and societal outcomes, alongside workplace readiness. Zollman (2012) describes this as not simply, "learning to *know* and learning to *do* (but also) learning to *live together* and learning to *be*" (p.15). However, this perspective requires a conceptualisation of STEM education as *not* existing within a single discipline but as a meta-discipline – one which integrates multiple knowledges into a new whole (Becker & Park, 2011; Kelley & Knowles, 2016; Morrison & Bartlett, 2009). Understanding STEM in this way opens possibilities for programs reflecting a more holistic view of STEM education for developing students' social, affective and cognitive capabilities, as well as deeper understanding of discipline knowledge (Bissaker, 2014; Hargrove, 2011; Madden et al., 2013).

At a classroom level, some authors indicated interdisciplinary STEM affords teachers freedom to plan and teach using pedagogies that more closely replicate 'real world' processes (e.g., Bennett & Monahan, 2013; Portz, 2015; STEM Task Force, 2014; Techakosit & Nilsook, 2018; Top & Sahin, 2015). These include project-based models that integrate disciplines and support students' STEM capabilities, skills and collaboration, through "meaningful activities that are relevant to real-world issues" (Capraro & Jones, 2013, p.52). Khan (2015) points out that authentic, interdisciplinary STEM projects present valuable opportunities to foster awareness and concern for the moral and ethical dimensions of STEM development. He suggests interdisciplinary approaches provide opportunities for students to critique and evaluate the implications and effects of both their own and others' STEM endeavours; building awareness of the value-laden nature of STEM decision-making through considering not only what "STEM can do, but also what STEM *ought* and *ought not* to do" (Khan, 2015, p.151).

Perspectives also varied on STEM discipline knowledge, which influenced views on how STEM education should be approached. For example, Oanh, Van Dung, Anh and Trang (2018) argue that in interdisciplinary STEM there is a risk that, "the motivation to produce an artefact, takes precedence over the development of science concepts" (p.1290), while others suggest, "students exposed to integrative approaches (to STEM) demonstrate greater achievement in the STEM subjects" (Becker & Park, 2011, p.31). Literature indicated differing perspectives on discipline knowledge broadly reflected in differing approaches to K-12 STEM education. Interdisciplinary STEM was viewed as a challenge to historical subject divisions and traditional ways of delivering and assessing curriculum (Holmlund et al., 2018; Marrero et al., 2014; Roberts, 2012), while single or dual discipline approaches were seen as more compatible (Hoachlander, 2014; Vasquez, 2014). Roberts (2012) comments that discipline divisions frequently contribute to STEM education being, "identified by the separate subjects of which it is composed" (p.1), nullifying what she saw as more holistic benefits from interdisciplinary approaches. Vasquez et al. (2013), however, suggests there are multiple, equally valid discipline 'entry points' to STEM education. They position discipline knowledge on a continuum starting with single-discipline orientation, working through multidisciplinary (concepts learnt separately but combined in a single project) and interdisciplinary (concepts learnt through integrating disciplines), to transdisciplinary (disciplines merge in solving authentic problems). Progression along the continuum indicates greater inter-dependence and inter-connection between the disciplines[1]. Interestingly, other literature identified Vasquez et al.'s *trans*disciplinary as *inter*disciplinary, suggesting there is some debate over terms used to describe similar approaches (e.g., Asghar et al., 2012; Honey et al., 2014; La Force, Noble, King, Holt & Century, 2014; Roberts, 2012).

Assessment of K-12 STEM education was viewed as problematic in much literature (e.g., Asghar et al., 2012; Honey et al., 2014; Mohr-Schroeder, Cavalcanti & Blyman, 2015). Specifically, difficulties with interdisciplinary assessment were noted due to current methods that predominantly focus on teaching and assessing conceptual understanding within a single discipline, with little attention being paid to the application of knowledge or how different knowledges integrate and contribute to solving authentic problems. This is compounded by moves in many countries towards 'high stakes' large-scale assessments, and difficulties designing assessments of this nature that adequately report on students' abilities to integrate STEM discipline knowledge, given the different ways these might be combined in problem or project-based curricula. Honey et al., also comment that interdisciplinary STEM assessment challenges teacher capability and expertise, raising the question of whether individual teachers, "must be responsible for (and have expertise in) multiple STEM content areas" (2014, p.120) and even if they do, whether they possess the pedagogical strategies to support students engaged in integrated learning experiences. Although general agreement existed that assessment of K-12 STEM education requires a balanced approach engaging formative, provisional and summative methods, few models or examples were presented illustrating how this could be achieved in classrooms. As Honey et al. observed, additional classroom-based "analyses of integrated STEM programs may reveal additional opportunities

[1] Detailed explanations of the continuum can be found in Vasquez et al., (2013), p.73-74 and at https://d41super.files.wordpress.com/2014/12/stem-beyond-the-acronym.pdf

for assessment" (2014, p. 130), and given increased emphasis on K-12 STEM education, research in this area should be prioritised.

In summary, literature displayed variation in its interpretation of, and rationale for, STEM education, and how it should be taught and assessed in schools. While workplace readiness featured prominently, priority given to this varied, with several authors arguing for a broader perspective reflecting more holistic outcomes across personal capability, affective and social domains. Perspectives on how K-12 STEM education might be taught ranged from approaches resembling existing discipline-oriented methods, to the complete integration of disciplines in project-based models, where knowledge was developed and applied according to the needs of projects. These perspectives reflected in different approaches to planning STEM curriculum, and different pedagogical designs. The following sections discuss the characteristics of these approaches, using the four concepts and themes - STEM capabilities, curriculum and pedagogy, discipline knowledge and literacy.

STEM Capabilities, Skills and Dispositions

There was broad agreement on the importance of capability, skill and disposition development as a component of, and outcome from, STEM education. Identified characteristics were coded under the themes of cognitive, creative, personal capabilities, and dispositions and attitudes. The characteristics, themes and descriptors are recorded in Appendix C, row 1. Skills generally aligned with Heckman and Kautz's (2012) definition of *soft skills*, that is, "personality traits, goals, motivations and preferences that are valued in the labour market, in school, and in many other domains" (p.451). They comprise problem solving, creative, critical and higher order thinking, collaboration, communication, teamwork, flexibility/adaptability, and personal dispositions and attitudes including risk taking, positive attitude towards failure, suspended judgement, and considering the impact of STEM on people and the environment (Bevan, 2017; Edwards, Perkin, Pearce & Hong, 2015; English, 2016; Heckman & Kautz, 2012; Honey et al., 2014; Land, 2013; Marshall & Harron, 2018). The relevance of skill development was a common theme, with one study claiming skills were of equal value to content knowledge and technical capabilities in economic terms, and also for fostering innovation (Balcar, 2016). Balcar's study concluded that content knowledge and technical capabilities (*hard skills*) by themselves were of limited value, claiming that, "the productivity of hard skills stems from their combination with soft skills" (p.453). This association was also noted in other literature (e.g., Honey et al., 2014; Zollman, 2012).

Some authors aligned STEM capabilities, skills and dispositions, with pedagogy and curriculum design. For example, perspectives were presented that skill development was dependent on learning environments where STEM-supportive dispositions and attitudes were encouraged, and where curriculum design and pedagogy strengthened their development (e.g., Capraro & Jones, 2013; Madden et al., 2013; Newhouse, 2017). These authors suggested learning environments play a significant role in facilitating or constraining STEM skill development. Newhouse (2017) noted that curricula that was overly prescribed and focused on detailed content, were less likely to support skill development and project-based models. Conversely, interdisciplinary approaches where concepts and knowledge were developed integral to a project, were seen as more supportive (e.g., Morrison, McDuffie & French, 2015). In summary, building students' learning independence, problem solving, higher order thinking and dispositions and capabilities, was viewed by all authors as residing at the core of STEM literacy.

STEM Curriculum and Pedagogy

Four themes aligned with the concept of STEM curriculum and pedagogy: curriculum and learning design, pedagogy, working processes, and design thinking. The themes, characteristics and descriptors are recorded in Appendix C, row 2. Overall, perspectives on STEM pedagogy favoured student-centred approaches, possibly reflecting the predominance of studies that advocated project-based, multi or interdisciplinary designs (e.g., Capraro & Jones, 2013; LaForce et al., 2016). Some authors, however, reminded that student-centred approaches still demand high levels of teacher engagement, which, at times, may mean adopting more instructive strategies as content or subject matter experts (e.g., Honey et al., 2014; Oanh, et al., 2018). The key message from these studies was that teachers should not make assumptions about their students' STEM knowledge and capabilities, but support their learning in different ways, reflecting students' needs and learning goals.

There was strong agreement in literature about the role of design thinking principles in K-12 STEM education. The importance of authentic, 'real world' projects focused on modelling or designing solutions to problems, needs, wants or opportunities, was represented across many studies (e.g., Bennett & Monahan, 2013; Bevan, 2017; Havice, 2009; Marshall & Harron, 2018; Sanders, 2012). Design thinking principles reflected in identifying a reason or motivation for STEM projects (problem identification), and as a structure to plan and teach to (design 'process') (Johns & Mentzer, 2016). Design thinking principles were integral to both discipline and interdisciplinary approaches, but differences existed in how some elements – particularly ideation and authenticity, were established. Authors promoting interdisciplinary approaches tended to see ideation as a starting point for STEM projects that were based on authentic problems, needs or opportunities (e.g., Bennett & Monahan, 2013;

Johns & Mentzer, 2016). The requirements of projects then provide direction and influence the selection and use of STEM (and other) discipline knowledge. Others recognising single or dual-discipline starting points, suggest first identifying target discipline knowledge, before developing a real (or created) theme, problem or context through which it can be learnt (e.g., English, 2016; Vasquez, 2014). Both approaches engage elements of design thinking - the fundamental difference being how discipline knowledge is operationalised within the design thinking process.

Discussion of STEM pedagogy included the teachers' role in establishing learning environments conducive to collaboration, creativity, innovation and skill development. Student exchange of knowledge and information and access to external information networks, were viewed as important for supporting STEM projects and skills - including research capability, teamwork, learner confidence, independence and self-organisation, and risk taking (e.g., Asghar et al., 2012; Land, 2012; Madden, 2013). Engaging stakeholders including community groups or businesses as participants in projects, enhanced the authenticity of STEM learning, and could assist with knowledge, resources or feedback as projects developed (Falloon, 2013, 2014; Shapiro, 2018). STEM projects of local relevance were considered effective for building student ownership and identity, and for raising awareness of the impact of STEM innovation on people and the environment (Honey et al., 2014). Finally, the importance of disseminating information about processes and outcomes from projects was considered valuable for building interest and understanding about STEM education in the community, gathering feedback useful for future projects, and for engaging parents, businesses and the community in school programs (e.g., Capraro & Jones, 2013; LaForce et al., 2016; STEM Task Force, 2014).

STEM Discipline Knowledge

Characteristics associated with STEM discipline knowledge were coded under the theme: discipline orientation (Appendix C, row 3). These aligned with authors' perspectives on learning specific discipline knowledge as a principal outcome from K-12 STEM education. Discipline orientation varied, with some authors suggesting, "there should be a focus on depth of content knowledge within a specific STEM discipline" (Mohr-Schroeder et al., 2015, p.10), while others argued "this (STEM education) means a reduced concern for covering content and an increased emphasis on helping a student learn" (Zollman, 2012, p.15). Discipline knowledge orientation influenced perspectives about entry points for K-12 STEM education. Some suggested single or dual discipline entry points (e.g., Oanh et al., 2018; Vasquez, 2014), while others supported interdisciplinary approaches focused first on a problem, need or opportunity, emphasising STEM education as being, "rooted in instructional practices, such as problem-based and student-centred learning" (LaForce et al., 2016, p.9).

Particular authors indicated interdisciplinarity can take different forms – that is, content (discipline), method, or process integration, varying according to different school levels, how schools are organised, and educational priorities (Becker & Park, 2012). Honey et al. (2014) suggested one discipline might assume a dominant role, with the others contributing to "support or deepen learning and understanding in the targeted subject" (p.42). This perspective reflected in approaches to STEM curriculum and pedagogy that focused on knowledge development in one or two disciplines, with problems or projects being identified or created around content to be learnt. The challenges associated with discipline orientation were highlighted in Asghar et al.'s (2012) study, where teachers expressed concerns that interdisciplinary methods threatened their ability to cover what they described as necessary "discipline-specific curriculum material" (p.106). While content concerns were not widespread, they did indicate difficulties some teachers associated with interdisciplinary STEM, especially when student learning was being assessed and reported as separate subjects.

In summary, literature debated discipline knowledge as an entry point or focus to STEM education. Views varied, ranging from emphasising discipline knowledge through to interdisciplinary project-based approaches, where knowledge is accessed, learnt and applied, *in situ*. While authors did not suggest a particular approach is preferred, they did highlight differences in how STEM education is conceptualised, which reflected in varied approaches to planning and teaching in the classroom.

STEM Literacy

Characteristics coded under this concept aligned with the theme: the goal and purpose of STEM education (Appendix C, row 4). These characteristics related to desired outcomes from K-12 STEM education, and comprised the knowledge, dispositions, capabilities and skills deemed important for students' productive engagement with STEM-related study, careers, issues and practices. STEM literacy represented the 'aim point' for K-12 STEM education, and was minimally-contested as a principal outcome from STEM curriculum. There was general agreement on its composition (i.e., what it means to be 'STEM literate'), although variation was noted in the emphasis given to its elements and outcomes.

For example, Cockle's (2018) review reported a strong emphasis on economic and workplace benefits, commenting:

> STEM is a pressing economic issue… (and what) counts as STEM literacy is a measure of the future-readiness of countries. The challenge of STEM learning is building capacity in learners to thrive in the 'known unknown' of future careers… (p.3)

This perspective generally reflected in position and policy statements including those published by the National Science Board (2015), The STEM Education Coalition (2014), The STEM Taskforce (2014), the Australian Industry Group (2015), and Australia's Office of the Chief Scientist (2016). These documents emphasised the economic importance of STEM education fulfilling the need for a 'skills pipeline' of workplace ready employees, possessing, "specialised skills in STEM and high STEM literacy across the board, to sustain economic growth" (Office of the Chief Scientist, 2016, p.2). Although broader benefits from a STEM literate citizenry were noted, unsurprisingly, policy and position papers more strongly emphasised economic and workplace-readiness outcomes.

Generally, empirical and conceptual work took a broader perspective, highlighting personal, societal and economic aspects of STEM literacy, with capability development across cognitive, affective and psychomotor domains (e.g., Breiner et al., 2012; Bybee, 2010; Honey et al., 2014; Zollman, 2012). These literature argued, "the need to go beyond content and beyond processes…(suggesting that) learning for STEM literacy may accomplish our societal needs and our economic needs, but what about personal needs to become a fulfilled, productive and knowledgeable citizen?" (Zollman, 2012, p.15). Zollman's perspective reflected in Bybee's (2010) work defining what he saw as four key elements to STEM literacy. They encompass learning in all three domains, and present a holistic perspective on the attributes and capabilities of STEM literate citizens.

Bybee's (2010) elements are:

- ability to develop and apply STEM knowledge to identify issues, acquire new knowledge, and solve problems;
- understand the characteristics of STEM endeavour, including inquiry, design and evaluation;
- recognise how STEM disciplines shape our intellectual activity and social, material and cultural worlds;

- engage with STEM challenges and disciplines as constructive and concerned citizens.

(adapted from Bybee, 2010, p.31)

There was consistent focus across literature on a STEM literate person as someone who understands and is able to apply STEM knowledge to life situations (e.g., Zollman, 2012); use STEM knowledge to solve or contribute to solving ill-structured problems (e.g., Asghar et al., 2012; Techakosit & Nilsook, 2018); communicate and understand information relating to STEM issues (e.g., Khan, 2015), and make informed decisions about STEM-related events or problems (e.g., Bybee, 2010; Ministry of Business, Innovation and Employment, 2014). However, Zollman (2012) points out that being *STEM literate* is fundamentally different to *STEM literacy,* commenting that literacy demands more than knowing *how* to do something, but also having the cognitive, affective and dispositional attributes and capabilities to *apply* that knowledge in practice. He claims K-12 STEM education must develop students' STEM *identity*, that empowers them to operationalise their STEM capabilities in ways that have positive impact and effect. Central to establishing STEM *identity*, Zollman identifies a critical role for teachers to, "create (engaging) classroom conditions that nurture student needs for self-determination… encourage student self-regulation behaviors… and support student peer relationships and achievement of collaborative social goals" (2012, p.17). The importance of both capability and affective elements to STEM literacy was widely-supported, and closely aligned with the teachers' role of designing appropriate STEM curriculum, environments and pedagogical practices (e.g., Sanders, 2012).

To summarise, while literature generally supported interdisciplinary K-12 STEM and suggested the approach was more conducive to the development of a holistic STEM literacy, there was less agreement on how this should be planned for and taught in classrooms. Debate centred on the role of discipline knowledge, which influenced both the 'entry point' and design of STEM curriculum, and to a lesser extent, pedagogical approaches that support STEM skills, dispositions and capabilities. The following section applies the key findings of this review to conceptualise a framework that it is hoped can guide the design of K-12 STEM curriculum, accommodating the range of perspectives represented in literature.

A Framework Guiding STEM Education in Schools

The development of STEM literacy was a unifying theme across literature. This was positioned at the core of K-12 STEM education, defining its purpose and desired outcomes from STEM curriculum. These outcomes can be summarised as: learning STEM discipline knowledge, recognising how STEM shapes our world, understanding the nature of STEM-based endeavour, and engaging constructively with STEM-related issues and challenges. While differences existed in the orientation of discipline knowledge, all literature argued the importance of engaging more than one discipline at some point, and locating STEM curriculum in authentic contexts focused on the resolution of problems, needs or opportunities. Elements of design thinking, including research, problem specification/definition and ideation featured prominently, and was frequently associated with discipline integration beyond STEM. Although broad agreement existed on the desirability of student-centred pedagogies and that these were generally more compatible with STEM skills and dispositions, there was recognition that teachers have a pivotal role in K-12 STEM education as subject matter experts, and in developing curriculum and learning environments optimising opportunities for building STEM capabilities. What follows is a framework that attempts to conceptualise how each piece of the STEM 'puzzle' fits and relates to others, providing practical guidance on key elements of STEM education, and how they can be combined in different ways towards achieving the common goal of students' STEM literacy.

Insert Figure 1: *A STEM literacy development framework for STEM education*

The framework attempts to map connections between the characteristics of K-12 STEM education, to conceptualise different approaches to planning and teaching STEM curriculum. It recognises the common goal of STEM literacy, but acknowledges that different entry points, discipline knowledge orientations and pedagogical approaches, can co-exist in interpretations of STEM curriculum. Embedded in the core are skills and dispositions identified as desired outcomes from STEM education. These relate to the four pillars of STEM literacy – knowledge, engagement, endeavour and awareness; defining the attributes of students with the skills, dispositions, knowledge and capabilities to be considered STEM literate. Their location in the core indicates their centrality to STEM learning, recognising their relationship with knowledge, dispositions and skills, and as a foci for planning and teaching. This bi-directional interaction is represented in Figure 1 by the diagonal double-headed arrows.

Surrounding the core and indicated by the stacked grey bars, are the four STEM disciplines. Of note is that the bars are ordered differently, with each discipline being identified as a possible entry point or emphasis for STEM curriculum. The order of the bars is not intended to represent a priority, hierarchy or degree of contribution, as disciplines will contribute to different extents, and in different ways. Multiple disciplines should contribute to

STEM education, but representing them in this way signals the prospect that one or two might serve as 'lead ins' to STEM curriculum. Pragmatically, this opens possibilities for teachers teaching discipline-structured curriculum, to explore the potential of using their discipline as a 'springboard' to more integrated approaches. This opportunity is illustrated by the double-headed arrows running across the bars depicting the integration of discipline knowledge, but using a single discipline as an entry point. For example, a Digital Technology teacher may require students to learn how to code using HTML5. While maintaining the focus on coding knowledge (Technology), the teacher might approach this using a project model that requires students to create websites for different client groups (created or real), all of whom have different budgets, needs and purposes, for their web presence. In another example, a Physics teacher might target specific concepts related to electron flow in circuits of different designs, through engaging students in researching and developing circuit schematics for buildings, designed to meet the specifications required by an identified client. STEM curriculum of this design will require students to research client priorities, develop briefs and plans of action, generate and evaluate prototypes, and assimilate client feedback – all of which draw on knowledge and skills beyond the original discipline. Such approaches enable teachers to meet discipline knowledge objectives, and for students to learn this through projects that are meaningful and provide opportunities to develop STEM literacy capabilities.

The upper half of the framework identifies a range of contexts or starting points for STEM curriculum, located in wants, opportunities, needs or problems. In curriculum of this design, the contribution of discipline knowledge is more aligned with the requirements of the project, potentially enhancing its authenticity and supporting students' understanding of the collective contribution of multiple disciplines to developing solutions and outcomes (interdisciplinary orientation). Their weaker association with single discipline orientation is indicated by the light grey arrow. The inwards pointing arrows indicate problems, needs, opportunities and wants as motivators or contexts for projects, engaging the inner ring of work processes (partnerships, knowledge exchange, networking, stakeholder engagement, teamwork, collaboration) and different 'blends' of discipline knowledge, in project-based designs. The lower half of the framework details curriculum, pedagogy and learning environment characteristics associated with the different discipline orientations. However, the organisation of these in the inner ring is not intended to communicate exclusive alignment with either interdisciplinary *or* discipline orientations. Instead, pedagogical and curriculum approaches will vary according to the nature and stage of STEM projects, and priority given to outcomes such as discipline knowledge and skill and competency development. In reality, STEM curriculum of either orientation will likely require different pedagogies, learning designs and teacher roles, at different times. While literature more strongly argued for interdisciplinary, student-focused designs, it is important that any framework is sufficiently flexible to accommodate other approaches. Finally, of note is the inclusion of design thinking in the outer ring. Its positioning recognises design thinking's role in pedagogy and curriculum of either orientation, reflecting consistency across literature indicating its principles as a commonly-applied structure and/or process in K-12 STEM education. Design thinking's trans-orientation role is indicated by its central placement, and arrows linking it to both orientations.

Conclusion: Opportunities, and Challenges

This framework attempts to conceptualise how the characteristics of STEM education might be combined and integrated in different ways in school curricula, focused on developing students' STEM literacy. It is not intended to depict an 'either-or' scenario, but rather encourage consideration of different approaches, strategies and roles, determined on a *fit for purpose* basis. However, implementing the framework is not without its challenges in current school environments where external standards, single discipline assessment and 'siloed' departmental structures, can nullify discipline integration efforts (Bybee, 2010). Tension also exists with national policy and curriculum, where teachers are being encouraged to explore interdisciplinary methods, while at the same time expected to report on students' STEM achievement as separate disciplines, often using rigid standardised testing (Timms, Moyle, Weldon and Mitchell, 2018).

Notwithstanding these challenges, examples of innovative, interdisciplinary STEM are emerging and reporting positive outcomes (e.g., Becker & Park, 2011; Madden et al., 2013; Morrison et al., 2015; Newhouse, 2017; Roberts, 2012; Sleap, 2018[2]). In these examples, schools have taken the opportunity to reconceptualise curriculum, making adjustments to historical organisational systems and structures to improve flexibility, collaboration and discipline integration supportive of new, project and problem-based STEM pedagogies. These illustrate that change towards interdisciplinary K-12 STEM education *is possible* within existing educational environments, and that doing so can yield significant benefits for holistic STEM literacy development. At the very least, this framework and analysis could be used as a starting point for discussion about how existing curricula might

[2] See Cessnock Academy of STEM Excellence (https://chslccase.org/)

begin to transition from isolated, single subject approaches, to ones reflecting the input of multiple disciplines in projects holding greater authenticity and relevance. To facilitate this in schools, it could be used in interfaculty or interdisciplinary planning meetings to audit existing courses, focusing on how they might evolve towards ones reflecting greater integration of the STEM disciplines delivered through more meaningful, project-based approaches.

The framework might also provide impetus for debate about the literacy goal of K-12 STEM education, stimulating evaluation of current curricula and pedagogies to determine their effectiveness and relevance for delivering the more holistic outcomes defined as someone being *STEM literate*. Future K-12 STEM education research has an important role to play in reporting and disseminating outcomes from these pioneering efforts, to build and share knowledge of effective practices in, and benefits from, integrated STEM education. Finally, the framework should be viewed as one attempt to help build understanding of STEM education and how it might be implemented in schools. The review revealed much debate about this, suggesting the foundation upon which accepted approaches and practices can be based, is still being established. Testing and evaluating the framework as a guide to planning and teaching K-12 STEM education, might assist in establishing this foundation.

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References

Anderson, S., Allen, P., Peckham, S. & Goodwin, N. (2008). Asking the Right Questions: Scoping studies in the commissioning of research on the organisation and delivery of health services. *Health Research Policy and Systems, 6*(7). https://doi.org/10.1186/1478-4505-6-7

Arskey, H. & O'Malley, L. (2005). Scoping Studies: Towards a methodological framework. *International Journal of Social Research Methodology, 8*(1), 19-32.

Asghar, A., Ellington, R., Rice, E., Johnson, F. & Prime, G. (2012). Supporting STEM Education in Secondary Science Contexts. *Interdisciplinary Journal of Problem-Based Learning, 6*(2), 85-125.

Australian Industry Group, (2015). Progressing STEM Skills in Australia (final report). Sydney: AIGroup. Retrieved from http://cdn.aigroup.com.au/Reports/2015/14571_STEM_Skills_Report_Final_-.pdf

Balcar, J. (2016). Is it Better to Invest in Hard or Soft Skills? *The Economic and Labour Relations Review, 27*(4), 453-470.

Becker, K. & Park, K. (2011). Effects of Integrative Approaches Among Science, Technology, Engineering and Mathematics (STEM) Subjects on Students' Learning: A preliminary meta-analysis. *Journal of STEM Education Innovations and Research*, 12(5-6), 23-37.

Bevan, B. (2017). The Promise and Promises of Making in Science Education. *Studies in Science Education*, *53*(1), 75-103.

Bissaker, K. (2014). Transforming STEM Education in an Innovative Australian School: The role of teachers' and academics' professional partnerships. *Theory into Practice, 53*(1), 55-63.

Brears, L., MacIntrye, B. & O'Sullivan, G. (2011). Preparing Teachers for the 21st Century using PBL as an Integrated Strategy in Science and Technology Education. *Design and Technology Education: an International Journal*, *16*(1), 36-46.

Breiner, J., Johnson, C., Harkness, S. & Koehler, C. (2012) What is STEM? A discussion about conceptions of STEM in education and partnerships. *School Science and Mathematics, 112*(1), 3-11.

Bybee, R. (2010). Advancing STEM Education: A 2020 vision. *Technology and Engineering Teacher,* (Sept.), 30-35.

Bybee, (2013). The Case for STEM Education: Challenges and opportunities. National Science Teachers' Association. Arlington: NSTA Press.

Capraro, M. & Jones, M. (2013). Interdisciplinary STEM Project-Based Learning. In R. Capraro, M. Capraro & J. Morgan (Eds.), *STEM-Project-Based Learning: An integrated science, technology, engineering and mathematics (STEM) approach* (pp. 51-58). Rotterdam: Sense.

Caprile, M., Palmén, R., Sanz, P. & Dente, G. (2015). *Encouraging STEM Studies in the Labour Market.* European Parliament Directorate General for Internal Policies [White Paper 542.199]. Retrieved from http://www.europarl.europa.eu/studies

Daudt, H., van Mossel, C. & Scott, S. (2013). Enhancing the Scoping Study Methodology: A large, inter-professional experience with Arskey and O'Malley's framework. *BMC Medical Research Methodology, 13*(48). https://doi.org/10.1186/1471-2288-13-48

Edwards, D., Perkins, K., Pearce, J. & Hong, J. (2015). *Work Integrated Learning in STEM in Australian Universities.* Final report submitted to The Office of the Chief Scientist. Retrieved from https://research.acer.edu.au/higher_education/44

English, L. (2016). STEM Education K-12: Perspectives on integration. *International Journal of STEM Education, 3*(3), 1-8.

Falloon, G. (2013). Forging School-Scientist Partnerships: A case of easier said than done? *Journal of Science Education and Technology 22*(1), 858-876.

Falloon, G. (2014). Using Videoconferencing in a School-Scientist Partnership: Students' perspectives and scientists' challenges. *Research in Learning Technologies*, *20*, 1-18.

Hargrove, R. (2011). Fostering Creativity in the Design Studio: A framework towards effective pedagogical practices. *Art, Design & Communication in Higher Education, 10*(1), 7-31.

Havice, W. (2009). The Power and Promise of a STEM Education: Thriving in a complex technological world. In International Technology and Engineering Educators' Association (ITEEA) (Ed.), *The Overlooked STEM Imperatives: Technology and Engineering* (pp. 10-17). Reston, VA: ITEEA Publications.

Heckman, J. & Kautz, T. (2012). Hard Evidence on Soft Skills. *Labour Economics 19*, 451-464.

Holmlund, T., Lesseeig, K. & Slavit, D. (2018). Making Sense of STEM Education in K-12 Contexts. *International Journal of STEM Education, 5*(32), 1-18.

Honey, M., Pearson, G. & Schweingruber, H. (Eds.). (2014). *STEM Integration in K-12 Education: Status, prospects and an agenda for research*. Washington DC: National Academies Press.

Johns, G. & Mentzer, N. (2016). STEM Integration through Design and Inquiry. *Technology and Engineering Teacher, Nov*, 13-17.

Khan, S. (2015). Another 'M' for STEM? Moral considerations for advancing STEM literacy. *K-12 STEM Education, 1*(4), 149-156.

LaForce, M., Noble, E., King, H., Century, J., Blackwell, C., Holt, S., Ibrahim, A. & Loo, S. (2016). The Eight Essential Elements of Inclusive STEM High Schools. *International Journal of STEM Education, 3*(21), 1-11.

Land, M. (2013). Full STEAM Ahead: The benefits of integrating the arts into STEM. *Procedia Computer Science 20*, 547-552.

Madden, M., Baxter, M., Beauchamp, H., Bouchard, K., Habermas, D., Huff, M., Pearon, J. & Plague, G. (2013). Rethinking STEM Education: An interdisciplinary STEAM curriculum. *Procedia Computer Science 20*, 541-546.

Marginson, S., Tytler, R., Freeman, B. & Kelly, R. (2013). *STEM County Comparisons: International comparisons of science, technology, engineering and mathematics (STEM). Final report.* Australian Council of Learned Academies. Retrieved from https://dro.deakin.edu.au/eserv/DU:30059041/tytler-stemcountry-2013.pdf

Marrero, M., Gunning, A. & Germain-Williams, T. (2014). What is STEM Education? *Global Education Review, 1*(4), 1-6.

Marshall, J. & Harron, J. (2018). Making Learners: A framework for evaluating making in STEM education. *Interdisciplinary Journal of Problem-Based Learning, 12*(2), Article 2. Retrieved from https://doi.org/10.7771/1541-5015.1749

Ministry of Business, Innovation and Employment. (2014). *A Nation of Curious Minds. A national strategic plan for science in society.* Wellington: New Zealand Government.

Mohr-Schroeder, M., Cavalcanti, M. & Blyman, K. (2015). STEM Education: Understanding the changing landscape. In A. Sahin (Ed.), *A Practice-based Model of STEM Teaching* (pp. 3-14). Rotterdam: Sense.

Moore, T., Stohlmann, M., Wang, H., Tank, K., Glancy, A. & Roehrig, G. (2014). Implementation and Integration of Engineering in K-12 STEM Education. In *Engineering in Pre-College Settings: Synthesizing Research, Policy, and Practices* (pp. 35-60). West Lafayette, IN: Purdue University Press.

Morrison, J. & Bartlett, B. (2009). STEM as Curriculum: An experimental approach. *Education Week, 8*(23), 28-31.

Morrison, J., McDuffie, A. & French, B. (2015). Identifying Key Concepts of Teaching and Learning in a STEM School. *School Science and Mathematics, 115*(5), 244-255.

Munn, Z., Peters, M., Stern, C., Tufanaru, C., McArthur, A. & Aromataris, E. (2018). Systematic Review or Scoping Review? Guidance for authors when choosing between a systematic or scoping review approach. *BMC Medical Research Methodology, 18*(143), 1-7.

National Research Council. (2011). *Successful K-12 STEM Education: Identifying effective approaches in science, technology, engineering and mathematics*. Washington DC: The National Academies Press. https://doi.org/10.17226/13158

National Science Board. (2015). *Revisiting the STEM Workforce.* National Science Foundation. Retrieved from https://www.nsf.gov/nsb/publications/2015/nsb201510.pdf

Newhouse, C. (2017). STEM the Boredom: Engage students in the Australian Curriculum using ICT with problem-based learning and assessment. *Journal of Science Education and Technology, 26*(44), 44-57.

Oanh, D., Van Dung, L., Anh, T. & Trang, N. (2018). STEM Education: Organising high school students in Vietnam using engineering design process to fabricate water purification systems. *American Journal of Educational Research, 6*(9), 1289-1300.

Office of the Chief Scientist. (2016). *Australia's STEM Workforce: Science, technology, engineering and mathematics.* Canberra: Australian Government. Retrieved from https://www.chiefscientist.gov.au/wp-content/uploads/Australias-STEM-workforce_full-report.pdf

Pham, M., Andrijana, R., Greig, J., Sargeant, J., Papadopoulos, A. & McEwan, S. (2014). A Scoping Review of Scoping Reviews: Advancing the approach and enhancing the consistency. *Research Synthesis Methods, 5*, 371-385.

Portz, S. (2015, April). *The Challenges of STEM Education.* Paper presented at the Space Congress, Florida. Retrieved from http://commons.erau.edu/space-congress-proceedings/proceedings-2015-43rd/proceedings-2015-43rd/3

Quinn, H. & Bell, P. (2013). How Designing, Making and Playing Relate to the Learning Goals of K-12 Science Education. In M. Honey & D. Kanter (Eds.), *Design, Make, Play: Growing the next generation of STEM innovators* (pp. 17-33). New York: Routledge.

Roberts, A. (2012). A Justification for STEM Education. *Technology and Engineering Teacher* (May-June), 1-5.

Sanders, M. (2012). Integrative STEM Education as "Best Practice". In H. Middleton (Ed.), *Explorations of Best Practice in Technology, Design & Engineering Education, Vol.2* (pp. 103-117). Gold Coast: Australia. Griffith Institute for Educational Research.

Salami, M., Makela, C. & deMiranda, M. (2017). Assessing Changes in Teachers' Attitudes Towards Interdisciplinary STEM Teaching. *International Journal of Technology and Design Education, 27*, 63-88

Shapiro, D. (2018). *Connecting Businesses and STEM Students*. National Science Teachers' Association. Retrieved from http://nstacommunities.org/blog/2018/10/04/connecting-businesses-and-stem-students/

Sleap, S. (2018). *The Cessnock Academy of STEM Excellence*. Retrieved from https://chslccase.org/

STEM Education Coalition, (2014). Statement of Core Policy Principles. Retrieved from http://www.stemedcoalition.org/wp-content/uploads/2014/04/Note-STEM-Education-Coalition-Core-Principles-2014-Final.pdf

STEM Task Force. (2014). *Innovate: A blueprint for science, technology, engineering and mathematics in California Public Education*. Dublin, CA: Californians Dedicated to Education Foundation. Retrieved from http://www.cde.ca.gov/pd/ca/sc/documents/innovate.pdf.

Techakosit, S. & Nilsook, P. (2018). The Development of STEM Literacy using the Learning Process of Scientific Imagineering through AR. *International Journal of Emerging Technologies in Learning, 13*(1), 230-238.

Timms, M., Moyle, K., Weldon, P. & Mitchell, P. (2018). Challenges in STEM Learning in Australian Schools. *Policy Insights 7*. Victoria: Australian Council for Educational Research. Retrieved from https://research.acer.edu.au/policyinsights/7/

Top, N. & Sahin, A. (2015). Make it Happen: A study of a novel teaching style, STEM students on the stage (SOS), for increasing students' STEM knowledge and interest. In A. Sahin (Ed.), *A Practice-based Model of STEM Teaching* (pp. 43-62). Rotterdam: Sense.

Vasquez, J. (2014). STEM: Beyond the acronym. *Educational Leadership,* (Dec-Jan 2014), 10-16.

Vasquez, J., Sneider, C. & Comer, M. (2013). *STEM Lesson Essentials, Grades 3-8: Integrating science, technology, engineering and mathematics*. New York: Heinemann.

Zollman, A. (2012). Learning for STEM Literacy: STEM literacy for learning. *School Science and Mathematics*, *112*(1), 12-19.

Figure

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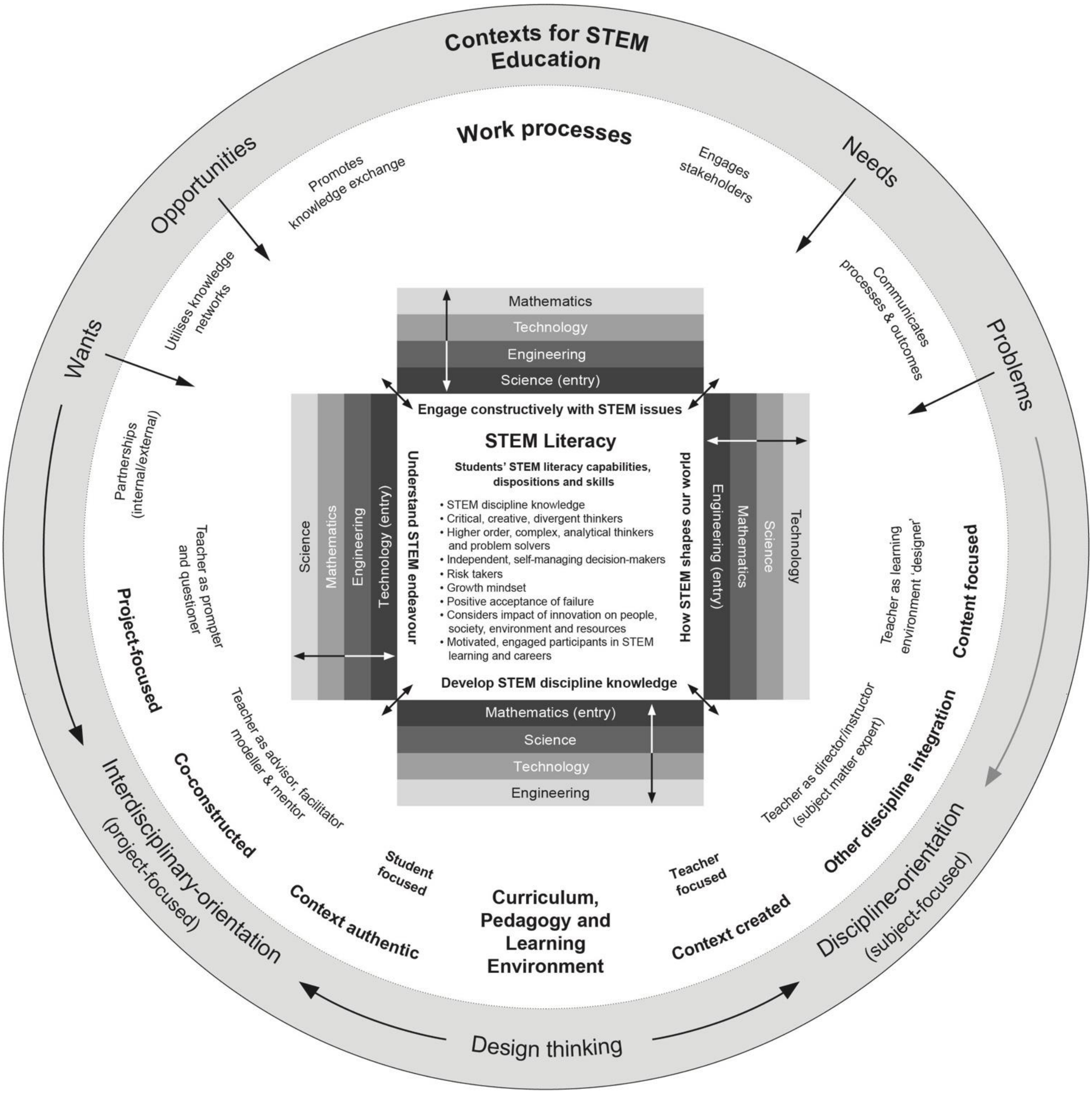

Figure 1. A STEM literacy development framework for K-12 STEM education