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Perspective

Centricities of STEM curriculum frameworks: Variations of the S-T-E-M Quartet

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Abstract: This commentary is an extension to the integrated S-T-E-M Quartet Instructional Framework that has been used to guide the design, implementation and evaluation of integrated STEM curriculum. In our discussion of the S-T-E-M Quartet, we have argued for the centrality of complex, persistent and extended problems to reflect the authenticity of real-world issues and hence, the need for integrated, as opposed to monodisciplinary, STEM education. Building upon this earlier work, we propose two additional variations—solution-centric and user-centric approaches—to the provision of integrated STEM curricular experiences to afford more opportunities that address the meta-knowledge and humanistic knowledge developments in 21st century learning. These variations to the S-T-E-M Quartet aims to expand the scope and utility of the framework in creating curriculum experiences for diverse profiles of learners, varied contextual conditions, and broad STEM education goals. Collectively, these three approaches—problem-centric, solution-centric, and user-centric—can afford more holistic outcomes of STEM education.

Keywords: S-T-E-M Quartet, problem-centric, solution-centric, user-centric

1. Introduction

As the definition of "STEM education" continues to evolve dynamically and takes on different forms across the world, there is heightened necessity for theoretically informed and evidence-based STEM conceptual frameworks to be developed to guide the integration of STEM disciplines in school curricula. A conceptual framework provides a representation of the relationships between different variables or aspects that make up the concept. When attempting to make sound curricular deliberations, frameworks offer a structure to unpack the complexities of STEM curricular designs and practice when situated within diverse contexts with unique challenges. Without frameworks to guide STEM curricular decision making, STEM education is at best, a trial-and-error endeavour by educationists in attempting to bridge school and real-world demands. To be clear, we refer to "STEM" as the science, technology, engineering and mathematics disciplines that have been integrated in multi-, inter-, or trans-disciplinary ways to harness the unique disciplinary knowledge and practices in the construction of an integrated form of knowledge and practices. Bryan, Morre, Johnson, and Roehrig [3] have argued that integrated STEM can be achieved through the integration of the practices of engineering and engineering design. However, others have also argued that the processes and practices of engineering and engineering design have useful roles beyond engineering and this has led to the co-construction of the S-T-E-M Quartet that incorporates the processes in problem-centric STEM inquiry to solve real-world problems that are complex, persistent and pervasive [28]. As we continue to trial our integrated STEM curriculum, designed using the S-T-E-M Quartet in the classrooms, we have identified limitations in problem-centric STEM curricular. As such, our ideas about the S-T-E-M Quartet—that offers a guide to the development of an integrated STEM curriculum underscoring the connections between the four disciplines—have evolved from being problem-centric to include other forms of centricities. The more comprehensive S-T-E-M Quartet will better address the diverse issues of integrated STEM curriculum implementation in the classrooms and to underscore the developments of other aspects of 21st century dispositions.

2. Holistic outcomes of STEM education

There are three important learning outcomes in holistic education ─ (1) foundational knowledge, (2) meta-knowledge, and (3) humanistic knowledge [16]. Foundational knowledge refers to conceptual knowledge within the various disciplines. For instance, the nature of insulin, where it is produced and its action on the human body, are foundational knowledge to help one understand diabetes. Having conceptual knowledge alone, is generally insufficient for the application of knowledge to solve problems and make one an expert in a specific field. Meta-knowledge—defined as reflection on the nature of conceptual knowledge and how it can interface with other knowledges to solve problems—is necessary to make conceptual knowledge useful or applicable. Students can develop meta-knowledge when they understand how and the conditions under which synthetic insulin can be used by patients to manage and control diabetes. The last type of knowledge that is necessary for holistic education is humanistic knowledge. Humanistic knowledge is defined as the human experience that result in rational thinking for moral decision making. Humanistic knowledge is important particularly in STEM education since it offers the basis for ethical and responsible problem-solving. As learners have diverse experiences, the development of humanistic knowledge is likely to be highly varied and hence, complex.

3. A scan of STEM curriculum frameworks

As mentioned earlier, frameworks are useful in curricular decision making. In this section, we review some existing STEM curriculum frameworks before discussing our proposed new variations to the S-T-E-M Quartet. In our scan of eight STEM curriculum frameworks, including the S-T-E-M Quartet, we have identified seven different types of centricities (see Table 1). By centricity, we refer to the integrating mechanism that brings together the four disciplines into a coherent form in the classroom to help learners appreciate and experience STEM education in a non-discrete manner. For example, the PIRPOSAL model (see Table 1, F#2) by Wells [32] is a questioning-centric model that positions question posing by learners as the initiator of all engineering design processes. Questioning supports convergent thinking (e.g., pulling together verifiable information to address the questions) and divergent thinking (e.g., identifying new questions with no obvious answers).

Table 1. Summary of STEM curriculum frameworks

Entry No.	Articles on STEM Curriculum Frameworks	Brief Description of Integration	Centrality of STEM
F#1	Thibaut, L., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A., Boeve-de Pauw, J., et al. [29]	Integration of STEM content, problem-centered learning, inquiry-based learning, design-based learning, cooperative learning	Not mentioned
F#2	Wells, J. G. [32]	PIRPOSAL Model based on engineering design PIRPOSAL is the acronym for: • Problem Identification • Ideation • Research • Potential solutions • Optimization • Solution evaluation • Alterations • Learned outcomes	Questioning - to initiate the engineering design processes, promoting convergent and divergent thinking
F#3	English, L. D., King, D., & Smeed, J. [9]	Framework based on engineering design	STEM disciplinary knowledge from each STEM domain
F#4	Asunda, P. A., & Mativo, J. [1]	Problem-based learning, pragmatism, and four theoretical constructs (systems thinking, situated learning theory, constructivism, and goal orientation theory) that blend together to accentuate Pedagogical Content Knowledge (PCK)	Problem-based learning
F#5	Kelley, T. R., & Knowles, J. G. [15]	Connections between situated learning, engineering design, scientific inquiry, technological literacy and mathematical thinking	Context
F#6	Glancy, A. W., & Moore, T. J. [11]	STEM Translation Model that proposes engaging the unique ways of thinking within each discipline and applying it to solve problems in another disciplines	Disciplinary thinking
F#7	Gale, J., Alemdar, M., Lingle, J., & Newton, S. [10]	Innovation Implementation Framework identifies the critical component of innovation and uses it for evaluating innovation implementation	Structural and interactional innovation components
F#8	Tan, Teo, Choy, & Ong [28]	S-T-E-M Quartet Instructional Framework on vertical and horizontal integrations within and across disciplines to solve authentic problems	Complex, extended and persistent problems

Out of the eight frameworks examined, five (F#1, F#2, F#4, F#6, and F#8) of them use problems or problem-solving as the integrating mechanism to connect the different STEM disciplines. Unlike exercises with questions that students could resolve immediately by applying a set of specific techniques, problem solving demands much more thought and resourcefulness before the right approach is found [35]. Similarly, by positioning problem solving as the integrative mechanism that binds all four disciplines, the S-T-E-M Quartet proposes the design and orchestration of STEM activities around a problem that offers applied learning experiences for learners [28]. The S-T-E-M

Quartet highlights the common iterative problem-solving processes that scientists, mathematicians, engineers and technologists engage as the means to frame these learning experiences. In another framework (F#3) by English, King and Smeed [9], they posited STEM disciplinary knowledge as the core of their framework and suggested using engineering-based problems to develop students' competencies in engineering design processes comprising the iterative process of problem scoping, idea creation, designing and constructing, and redesigning and reconstructing.

The problem-solving process thus creates opportunities for learners to understand the problem in depth, generate plausible solutions, evaluate solutions and weigh trade-offs, test solutions, review solutions and subsequently improve upon the proposed solutions. The focus on complex, persistent and extended problems coupled with the problem-solving process allows for learners to apply their disciplinary knowledge, together with disciplinary practices, to generate solutions. Further, engagement with complex and persistent real-world problems provide opportunities for learners to engage in collaborative discussions, group critique, and also defend their ideas. Although a problem-centric approach shows promise in integrating the STEM disciplines as a coherent curriculum, it is not the only way to conceptualise STEM curriculum integration through problem solving. In particular, we wonder if and how educators can approach integrated STEM education through other aspects of problem solving.

In this commentary, we build on earlier discussions about integrated STEM education, informed by the S-T-E-M Quartet (Figure 1, [28]), to explicate the notions of a solution-centric and a user-centric approach to STEM education. We have argued that using problems as the integrative mechanism for STEM allows learners to appreciate the connections (epistemic knowledge and practices, social norms and conceptual understanding) between the four disciplines as they work on plausible solutions. However, in the context of problem solving, it is also possible to start with existing solutions and engage in the iterative processes of evaluating current solutions, reflecting on the 'gaps' of current solutions, generating improved solutions, and testing new solutions. A solution-centric integrative mechanism for STEM can provide learners opportunities to engage more productively and extensively in the 'looking back' phase of problem solving [23], which is often neglected in many problem-solving activities.

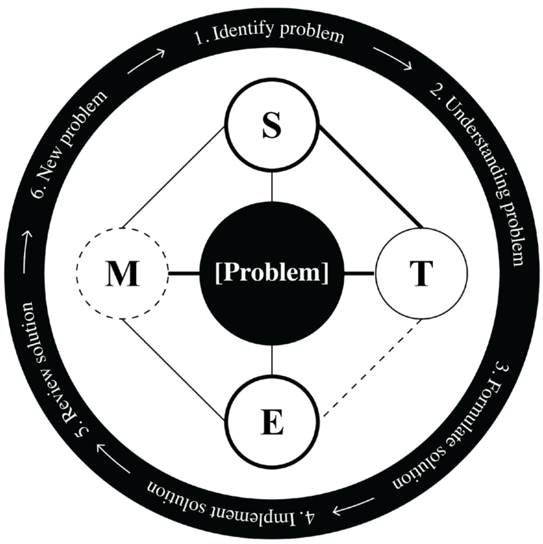

Figure 1. Problem-centric integrated STEM instructional framework [taken from 28]

Yet, another way to think about real-world problem-solving process is to start with the user. In a user-centric approach, the user becomes the starting point to drive the iterative processes of understanding the user and context, ideating solutions for the user, creating solutions for the user, and evaluating solutions with the user. By proposing two other approaches, we do not intend to replace a problem-centric approach to integrating STEM. Instead, what we are proposing is to complement the problem-centric approach with the solution-centric and user-centric approach to develop a more comprehensive system of integrating STEM education through problem solving. In this paper, we will first review the challenges of a problem-centric approach, explain the solution-centric and user-centric approaches, compare the three approaches, illustrate how these approaches can be incorporated in STEM lessons, and highlight the implications of these approaches for both practitioners and STEM education researchers.

4. Challenges with implementing a problem-centric S-T-E-M curriculum

Problem-centric STEM starts with understanding a complex, persistent and extended problem within its unique context. While the intent of problem-centric STEM is to afford students an authentic experience in tackling real-world problems, learners typically have to spend time unravelling the problem from the context [12] before an appropriate and plausible solution can be designed. The different ways of interpreting the problem and context also means that it is possible for learners to identify different yet equally important problems to work on. This could potentially generate two related issues in learning and teaching, especially when there is a lack of proper structures to guide students in approaching the problem.

First, it has been argued that learning may be ineffective and inefficient if the problem is novel for students and there are no proper supporting structures to scaffold the learning experience for students. Empirical studies that support learning with minimal instructions are vast but lack robustness in presenting direct evidence to show that learning has taken place [21,22,26,27]. The literature [26,27] on human cognitive architecture that examines how cognitive structures are organised has informed us that free exploration in a highly complex environment, in contrast to worked-examples practices, may generate heavy working memory load and hence, become counterproductive to learning.

Second, from a practical standpoint, teachers may be swarmed by a myriad of ideas that students present to solve a problem. This poses a practical challenge to teachers who may feel unprepared to tackle the whole suite of possible solutions that students suggest. As such, teachers may not be able to provide all the necessary resources to support students' experimentation to trial their solutions. For instance, in our current work, one of the problems that we posed to students was to ensure sufficient crop yield in a land scarce country such as Singapore. The teachers had planned for the students to generate solutions that were largely linked to the concept of vertical farming designs to maximise the rate of photosynthesis of plants. The materials and resources prepared for students to trial their solutions were hence, based on the designs of vertical farms. However, after intensive discussions, one group of students suggested that CRISPR (clustered regularly interspersed short palindromic repeats) gene technology—a simple gene editing tool that can be applied to correct genetic defects to improve crops—should be applied to the crops to shorten the time needed for the plants to mature. With the life cycles from germination to harvesting of the crops shortened, the crop yield would also increase per unit time. While this was a highly plausible solution, the teacher was not prepared for such a solution and hence, unable to facilitate the trialling of this solution. The challenge posed here is that, it is not possible for a teacher to plan for all possible solutions, no matter how comprehensive the planning is.

In another example to illustrate how expansive the solutions could be, we have illustrated in the S-

T-E-M Quartet paper a problem-centric approach using an example of a STEM lesson that is based upon a real-world issue of increasing global trends in the number of diabetes patients. While there are several known solutions to address the problem of diabetes, other issues such as dietary preferences and habits, which are strongly connected with cultures, have resulted in a problem that is more complex to solve. The problem is persistent due to a lack of understanding of the confounding factors related to the condition, as well as the difficulty in changing lifestyles and food habits that define specific cultures. The complexity of problems and the multitude of possible solutions contributed to the challenges faced by teachers when they facilitate discussions and orchestrate learning opportunities to make the STEM experience directly relevant to learning outcomes stated in the school curriculum.

In essence, a problem-centric way of conducting integrated STEM lessons resembles a divergent curriculum and teachers feel insecure when they perceive themselves to be poorly equipped with the content knowledge to effectively facilitate the discussion and learning or to scope the content to make it relevant to the current school curriculum [18,20]. Teachers are uncertain if the solutions that learners propose would ‘fit’ the intended learning outcomes identified for the lessons. Feelings of loss over classroom and curriculum control can deter teachers from wanting to try out the idea of integrated STEM teaching. In fact, implementation of integrated STEM lessons that start with problems required some foundational support such as support from STEM instructional leaders, curriculum leaders to model instructional practices and school leaders to model and support risk taking [19].

In our ongoing efforts to expand on our knowledge about integrated STEM curriculum design and to address teachers’ concerns about the expansive nature of a problem-centric instructional approach, we propose two alternative approaches to integrated STEM design and implementation without compromising the quality of the integration of the disciplines. In the next section, we discuss solution-centric and user-centric STEM approaches – both have not been discussed in the context of STEM curriculum frameworks. In totality, the three approaches can holistically address the three learning outcomes in holistic education.

5. Solution-centric S-T-E-M Quartet

In solution-centric STEM, students work with a specific solution to a problem by understanding the affordances of the specific solution, the limitations of the solution and seek to understand how the solution can be redesigned for improvement. Here, we assume that existing solutions have limitations and students will analyse the limitations and think of ways to improve them. Harnessing the ideas from informed design, teachers could plan integrated STEM lessons starting from an *existing solution* to a problem rather than the problem itself. Such instructional design offers relatively more structures than the problem-centric lessons and in part, addresses the criticisms of ineffective and inefficient open inquiry lessons [17].

To illustrate the difference between starting from a problem and starting with a solution, let us go back to the example of the problem to increase crop yield. Taking a solution-centric way, students will be presented with a specific design of a vertical farm where they will work on identifying the affordances and limitations of the vertical farm design to increase crop yield. Here, the improvement of existing design forms the focus rather than the larger context of the problem. Similarly, for the diabetes problem, instead of presenting learners with the problem of the elderly who is diabetic and asking learners to design a solution to the problem, learners could be presented with an insulin pen that the elderly patient uses, evaluate its design and propose new ways to improve upon the design for better drug administration. As the learners work through modification of the design, they would engage in identifying constraints, exploring feasibility, identifying important features, and determining how the new design would improve on the existing designs. Hence, solution-centric STEM focuses on design improvement.

Design is an important aspect of deriving solutions in engineering practice. Bucciarelli [4] opined that design knowledge and knowing are essential elements of an epistemology of engineering. Besides performance-based project that challenges students to create a product or present their answers to demonstrate their knowledge, skills and attitudes [25], design challenges have been used in the teaching of mathematics [13] and design and technology [2]. Such design-based learning has the potential to improve students' growth mindset [34], creativity [7], and computational thinking [14]. Engagement in the design process requires students to be actively creating, thinking, anticipating problems and optimising their ideas. By engaging in the design process, learners learn to draw or represent their ideas, annotate their ideas and subsequently include details such as dimensions and instructions on how their ideas, models, prototype work. These design processes are keenly aligned with the intentions of 21st century learning of meta-knowledge comprising creativity thinking, critical thinking, and problem solving.

Crismond and Adams [6] characterised seven dimensions of informed design: (1) learning while designing, (2) making knowledge-driven decisions, (3) working creativity to generate design insights and solutions, (4) perceiving and taking perspectives intelligently, (5) conducting sustained technological investigations, (6) using design strategies effectively, and (7) connecting and reflecting on knowledge and skills. These seven dimensions were subsequently mapped onto a matrix pattern for novice and expert learners in nine domains: (1) problem solving vs problem framing, (2) skipping vs doing research, (3) idea scarcity vs idea fluency, (4) surface vs deep drawing and modelling, (5) ignore vs balance benefits and trade-offs, (6) confounded vs valid tests and experiments, (7) unfocused vs diagnostic troubleshooting, (8) haphazard or linear vs managed and iterative designing, and (9) tacit versus reflective design thinking. Therefore, the seven dimensions of informed design present a means for learners to focus on learning the various disciplinary knowledge when being engaged in generating creative improvement to existing solutions to problems. In fact, English and King [8] found that students' application of disciplinary knowledge occurred more frequently in the last two phases of the engineering framework of design evaluation and redesign. English and King's [8] empirical findings highlighted the need for students to reach the final phases of design to enable the science and mathematics ideas to emerge. Figure 2 represents the solution-centric STEM curriculum framework that underscores the idea of emergence of considered solutions embedded within a contextual problem. The students are first presented with a known solution to a problem. They will understand the problem by taking into consideration the context such as issues that are unique to the situation in which the solution is applied. They will then bring in relevant concepts from science, technology, engineering and/or mathematics to derive a better solution. Similar to Figure 1, the different lines denote the strength of connections between two respective disciplines. For example, it may be the case that understanding the various affordances of technology available (denoted by the thick line from T to V1 Solution in Figure 2) has a more direct bearing on refining the solution than understanding the mathematics behind the solution (which is denoted by a dotted line). Likewise, proposing a refined solution may draw more on connections between science and engineering (denoted by the thick lines between S and E in Figure 2). During the process, students may tap into these inter-disciplinary connections, acquire new ideas, and apply them to come up with gradually improved solutions.

Presenting students with existing solutions and engaging them in a discussion on the affordances and limitations of current solutions enables teachers to scope the learning activity in two ways: (1) learners work only with one existing solution and hence, teachers can more accurately identify the intended learning outcomes; and (2) learners can engage with more focussed discussions on design affordances specific to one solution. Taking this stance, teachers are able to plan the discussions and resources more accurately and this helps to boost the confidence of teachers in their planning and implementation. Teachers also have greater control over the learning outcomes since they are able to choose and present the students with specific solutions that matched the intended learning outcomes.

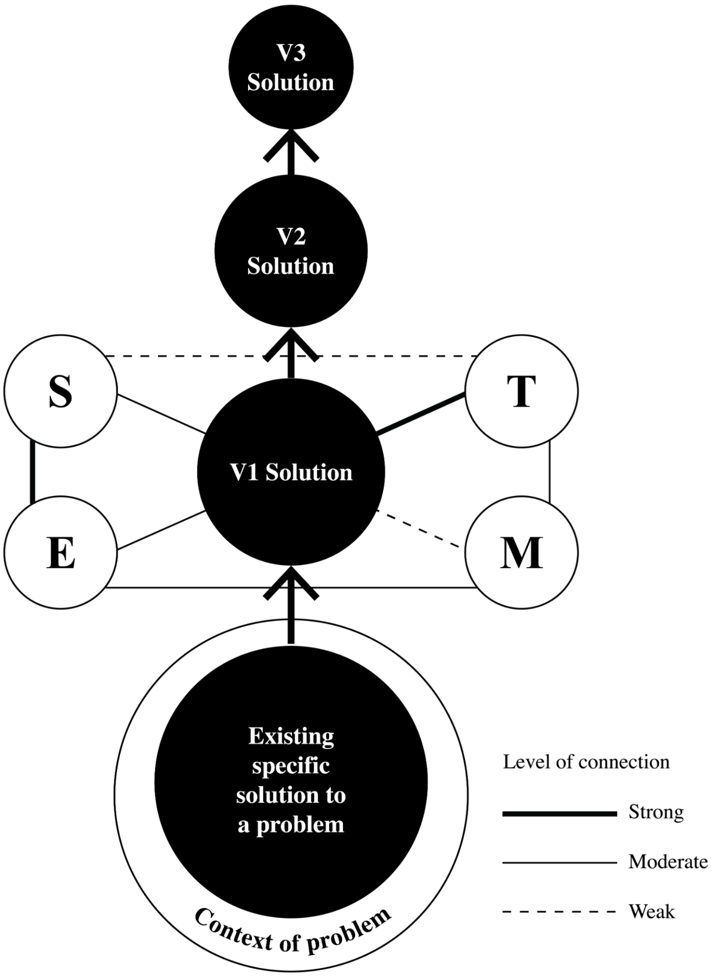

Figure 2. Solution-centric integrated STEM instructional framework

5. User-centric S-T-E-M Quartet

Contrary to the problem- and solution-centric curricular, a user-centric curriculum is one that prioritises the needs of the user of an outcome or output (e.g., product). Such an approach focuses on developing effective and efficient strategies to address specific goals satisfactorily for the user within the context of its use [31]. In user-centric STEM, learners pay attention to users' evaluation of the proposed solutions. In designing solutions, Winter [33] proposed a four-part problem-solving pattern of *Situation*, *Problem*, *Solution* and *Evaluation*. Here, the proposed solution to the specific problem is subjected to evaluation and subsequent refinement based on evaluation by specific users. This four-part pattern was adapted by Hoey [12] when he proposed to replace Solution with Response ─ only when the response is positively evaluated will it be considered a solution. Hoey illustrated his idea of "response-positive evaluation becomes solution" using the story of Goldilocks. Goldilocks was lost in the woods (this is the Situation), she became hungry (Problem), she ate Papa Bear's porridge

(Response) and found it too hot (negative Evaluation). Then we go back to the problem since Goldilocks is still hungry. When Goldilocks ate Baby Bear's porridge (Response), she found it just right (positive Evaluation). Hence the solution to Goldilocks hunger was to eat Baby Bear's porridge. Hoey's idea of response-evaluation places the user at the centre of any proposed 'solution' or responses. A proposed 'solution' is only good if the user finds it useful and evaluate it positively. One user may evaluate the response positively while another may evaluate it negatively. As such, evaluation to responses may be different and learners' awareness of specific users' evaluations and concerns can help with improvements of design of proposed ideas.

User-centric approaches, driven by user-centred evaluation to address the whole user experience in relation to the tasks and contexts [30,36], offer insights into how a user-centric STEM curriculum may look like. General phases of the user-centric approach basically entail: (1) specifying the context of use, (2) specifying the requirements or user goals, (3) creating design solutions, and (4) evaluating designs. Figure 3 below shows user-centric processes in user-centric STEM. The problem-solving process is multi-staged and engages problem solvers in researching about and imagining how users in a particular context (e.g., homes for people who are physically challenged and residential estate with high numbers of elderly) are likely to consume a product, while validating their ideas with the users to enhance product usefulness and usability. In the Design Thinking Process developed by the Hasso-Plattner Institute of Design at Stanford University, "empathise" is the first stage to the human-centred design process. Similarly, we underscore the importance of humanistic knowledge in the user-centric STEM instructional framework.

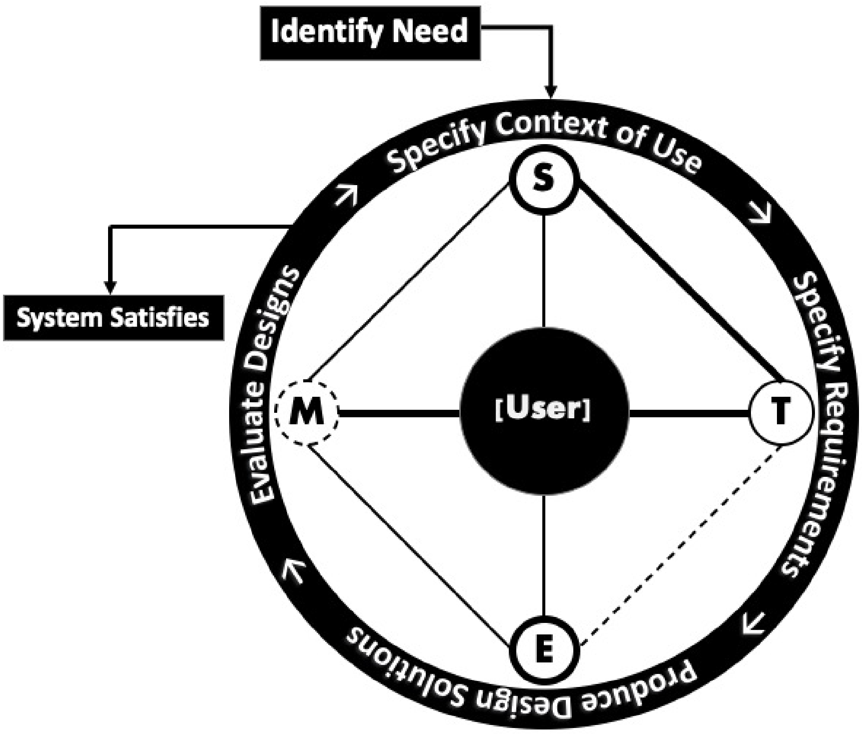

Figure 3. User-centric integrated STEM instructional framework

Returning to the example of the diabetes problem that is used to anchor an integrated STEM lesson, a user-centric STEM foregrounds the beneficiaries of the solutions to the diabetes problem. Imagine a lesson where students were tasked to think about the solutions for problems that diabetes patients confront. Students may not have the experience and relevant knowledge to identify such solutions and hence, focus their time and effort on solving a less pertinent issue affecting diabetes patients. This highlights the point that the solutions should be considered in relation to the contexts in which the users are situated. Students will have to reach out to the diabetes patients to find out their actual concerns and problems because they will provide their evaluation of the solutions. For example, users of the insulin pen must be knowledgeable about ways to handle the pen correctly and safely. While insulin pens are designed to deliver multiple doses of insulin for single users, there have been cases of misuses in hospitals that resulted in the use of insulin pens with different patients, exposing them to possibilities of HIV and Hepatitis infections [24]. While such mistakes are avoidable, it also raises questions about ways to produce single-use versus single-user insulin pens that are affordable and not wasteful. For patients who are elderly and in households with more than one elderly persons, using the insulin pen designs that ensure such problems do not arise become pertinent. Teachers can invite students to brainstorm scenarios where such possible mix up and other abuses and misuses of insulin pen may happen and the contexts in which these may occur. Then they can design solutions that address the same problem of misuses of insulin pen in different contexts (e.g., hospitals, elderly persons homes, and so on). Such an approach will ensure that the solutions are responsive to users' needs and are more likely to be adopted by the intended users. Through the process of participating in user-centric STEM curriculum, learners will learn to develop greater empathy for communities of people around them.

6. Comparison of the three approaches

Problem-centric and solution-centric STEM learning experiences are likely to result in the development of strong foundational knowledge and meta-knowledge since learners have to learn the foundational knowledge and decide which and how the knowledge can be applied to solve the problems. However, there is less emphasis on how solutions and improved design could affect different types of users. A user-centric STEM education experience can be incorporated to strengthen the development of humanistic knowledge. As the starting point of user-centric STEM is to develop a deep understanding of users, learners are required to consider the environment that the users live in, consider how the users interact with various elements in their environment, and empathise with the unique challenges that users face individually and as a community.

There are some similarities between the problem-centric and solution-centric integrated STEM learning experiences. Firstly, both learning experiences allow learners to learn and apply foundational knowledge such as core content knowledge and cross disciplinary knowledge. Specific foundational knowledge is used when students are understanding the problems, evaluating the solutions, critiquing design and presenting how specific solutions work. In both problem-centric and solution-centric learning experiences, learners are presented with the opportunity to become creative and critical thinkers as they design, re-design and improve upon their solutions. Similarly, as learners present their ideas, they learn to communicate, negotiate and persuade others of the benefits and superiority of their ideas.

Despite the similarities, there are two fundamental differences between learning experiences focusing on problems or solutions. Firstly, problem-centric learning experiences are more divergent since the solutions generated are varied and may not even be STEM in nature (for instance, to reduce diabetes, a law to ban all sugary food or a heavy sugar tax can be imposed). Students would be able to debate and consider the advantages and disadvantages of STEM-based solutions and compare them against non-STEM-based solutions. This could potentially raise greater awareness of the affordances and limitations of STEM solutions to real-world problems. Secondly, a focus on design refinements of existing solutions rather than problems allows students to engage in more iterative cycles of improvement and this could potentially result in revised prototypes that are of higher quality, which could result in greater motivation for improvements among the learners.

In summary, the affordances of problem-centric and solution-centric learning experiences foreground the learning of foundational knowledge and meta-knowledge. There is, however, less emphasis in these two modes of learning on humanistic knowledge of life/job skills, ethical/emotional awareness and cultural competences. As such, to augment the learning of humanistic knowledge, a user-centric approach can be an alternative for designing integrated STEM learning experiences. One of the main strengths of a user-centric STEM curriculum is its contributions to a more humanistic STEM education. To quote Coghlan and Brydon-Miller [5], "As a mindset, humanism [sic] denotes a level of education through which the individual is empowered to take care of himself or herself, cura sui, and to act responsibly on behalf the community, the communitas" (p. 2).

Table 2. Comparison of the problem-, solution- and user-centric S-T-E-M Quartets

	Problem-Centric	Solution-Centric	User-Centric
Focus	Complex, extended, and persistent problem	An existing solution to (part) of a complex, extended, and persistent problem	The existing and potential users of the outputs of the STEM solution
Types of knowledge prioritised in 21CC framework	Meta Knowledge: Students may think creatively on different ways to solve the problem collaboratively	Foundational Knowledge: The solution may be well-defined and core content knowledge and cross-disciplinary knowledge are pre-identified (e.g., use of technology as a requirement).	Humanistic Knowledge: Development of empathy in designers can be an outcome of the process.
Beneficiaries of the outcomes and outputs of engaging each model	The learners get to explore alternatives and develop a range of solutions for people to choose from.	The process is systematic, and resources may be sourced and provided to systematically test the feasibility of the idea.	The product is based on what users want, need or can use. They are not forced to change their behaviour and expectations to accommodate the product. Their needs are better met.
Limitations of the outcomes/outputs of engaging the various models	Wide range of solutions may be derived that may not be pragmatic unless tested and evaluated	The solution or approach may become too well-defined and limits creativity and innovation.	Individual needs are diverse hence, the product may not meet the needs of a large group of beneficiaries.

Table 2 shows the comparison between the three frameworks discussed earlier. As shown, each has its own affordances and limitations. The question is: *As teachers, how do we know which framework to choose to guide the implementation of integrated STEM in the classrooms?*

7. Curricular deliberations on the choice of frameworks

To reiterate a point made earlier, frameworks can be useful in informing theory and practice as they enable unique pieces of a complex puzzle to be carefully studied individually as well as in relation to the big picture. It can be harnessed as a thinking and planning tool to make decisions even as one learns more about a topic. Many schools around the world and in Singapore have embarked on some form of

STEM programmes, especially in robotics. As the schools' STEM programmes mature over time and new STEM curriculum emerge, teachers are beginning to wonder: Should we continue to offer our robotics programme? Besides robotics, what other types of STEM curriculum can schools offer to students? What is the best way to implement STEM lessons? Our view is that the choice is dependent on the students and the intended outcomes of the STEM lessons. We illustrate this with three cases we have observed in working with schools that have implemented STEM programmes.

> ***Case 1***: The students have no exposure to cross-disciplinary knowledge as their lessons are mostly subject-based (e.g., mathematics, science, English, social studies, etc.). In the school curriculum, the majority of the students have limited opportunity to engage in informal curriculum that exposes them to the real world applications of STEM subjects. The teacher intends to design an integrated STEM curriculum for the students to expose them to interdisciplinary thinking. However, the teacher has limited knowledge beyond his/her subject domain and prefers to retain control over how the curriculum develops.

> ***Case 2***: The students have some integrated STEM experience during their robotics lessons. They have exposure to MicroBits that made use of intuitive coding software to control sensors. The students also have exposure to the idea of the Internet of Things. In the previous school semester, they have participated in a school competition on making the fastest robot to move around in an obstacle course. The STEM curriculum culminates in that competition.

> ***Case 3***: A group of students in a school have exposure to coding and knows how to use the coding software, Python. They participated in the school's independent student inquiry research project that tasked them to develop solutions for the school's security team. The students decided to make use of their knowledge on coding and machine learning to create an app that can assist the security guards in tracking the cars parked on the school premises.

All these cases are examples that we have seen in our research studies in schools. Cases 1 and 2 are commonly encountered as schools were trying to embark on STEM education for the first time or have engaged external vendors to conduct robotics lessons (very common in Singapore schools) to enthuse students. In Case 1, we recommend that the teachers adopt the solution-centric approach to STEM to scope and scaffold the integration experience for students. With this experience, teachers will gain greater confidence with STEM integration as they are better equipped with the knowledge to anticipate students' questions and actions. In Case 2, we recommend that the teachers adopt the problem-centric approach to STEM because the students have the potential solution (know-how to use the software and manipulate the hardware), but their learning was prematurely truncated as they did not move on to think about the real life applications of robotics. Having this extended discussion about a problem and then seeing that making robotics could be one possible solution to the problem and that there are better alternatives around, will value add to students' integrated STEM learning. In Case 3, the students have the foundational and meta knowledge from integrated STEM fields. However, they did not consider the need to speak with the school security team to find out their needs prior to deriving the solutions. In that particular case, it was the teacher who suggested to the students to have a conversation with the security team and it was then that the students found out that they did not know what important questions to ask. Through conversations with the security team, students better understood the needs and limitations of the elderly security guards who were policing the cars parked all around the expansive school campus. Following that conversation, they designed an app that addressed the security guards' needs (e.g., larger font size).

While many (and more) STEM curriculum frameworks, models, and approaches have been and will be proposed to guide the design, implementation, and evaluation of STEM lessons, ultimately, it is a holistic education that STEM education originally sought to achieve. This goal extends beyond what the current mono-disciplinary curricular can afford to learners in the bid to develop 21st century competencies. We do not propose that STEM educators randomly pick either the problem-, solution- or user-centric STEM instructional framework to guide their STEM curriculum making. Rather, we recommend a purposeful selection of one or more of the frameworks and this "purposefulness" should be informed by careful deliberation and consideration of the STEM curriculum goals. If the purpose, for instance, is to improve students' ability to problem-find and to problem-solve because the regular curriculum does not afford them such experiences, then perhaps the problem-centric STEM instructional framework may be useful as a guide. However, if the teachers find problems coping with the divergence of a STEM lesson grounded in real-world problem, then perhaps offering students a solution to work on in a solution-centric STEM lesson may be more pragmatic and feasible. However, if students have demonstrated efficacy in problem-finding, problem-solving and deriving solutions, but have to build up greater community awareness, then perhaps the user-centric STEM curriculum may help to fill this gap in their overall learning experience.

8. Implications for research and practice

As we have argued in this commentary, the key to integrating STEM in ways that enable students to engage in different, yet authentic STEM problem-solving learning experiences is through careful deliberations about the three possible approaches highlighted. Doing so will require teachers to reflect on their own knowledge base and teaching contexts by thinking about their own mindsets to STEM integration. The three approaches highlighted are not just theoretical frameworks. They are practical tools that teachers can use to examine their STEM lesson ideas in greater depth. The different processes highlighted in the three frameworks can support teachers to think about both the intra-disciplinary and inter-disciplinary dimensions of curriculum design. In making choices on which framework to engage by weighing the diverse goals of STEM education, teachers will develop their professionalism and deepen their inter-disciplinary understandings in STEM curriculum making.

On the research front, there are several pieces of the puzzle that require serious attention. First, central to the core of each of these approaches is the knowledge base and mindset of teachers. What kinds of knowledge base are needed? What kinds of orientations are productive towards effective design and implementation of such integrated STEM lessons? Second, related to the question about knowledge and beliefs, is the professional development of teachers. How can STEM educators use these three approaches to develop the competencies needed by teachers to design and enact these learning experiences for their students? Last but not least, how do we know that STEM lessons designed and implemented according to these approaches actually work? And when we say they work, what do we actually mean?

9. Conclusion

In this commentary, we presented two variations to the design of integrative STEM learning experiences to achieve more holistic learning experiences for students. We described and compared problem-centric, solution-centric and user-centric STEM approaches. Each approach is characterised by a different starting point and objective. The three approaches offer teachers alternatives to plan their STEM lessons. The key reason for describing the approaches separately rather than to develop a framework encompassing all the three approaches is to make the planning and implementation of STEM lesson manageable and focused. Intentional planning and attention paid to the development of specific skills and disposition could potentially help learners and teachers develop a more acute sense of problem-solving, solution refinement and user experiences. Our emerging ideas of the S-T-E-M Quartet is inspired by the expanding emphasis on STEM education as the driver to achieving global competencies for the current and future generations of people to support a nation's economic and social goals. This dynamism in the conceptualisation of STEM education is a necessity even as the STEM education community seeks to derive a common understanding and identity about "STEM" simply because we are operating in a *glocalised* world, that is, a world that is simultaneously universalised and interconnected yet, bears unique characteristics that makes the phenomenon situated.

References

1. Asunda, P.A. and Mativo, Integrated STEM: A new primer for teaching technology education. *Technology and Engineering Teacher,* 2016, 76(5): 14-19.
2. Barlex, D., *Young foresight: Handbook for teachers and mentors*. 2000, London: Software Production Enterprise.
3. Bryan, L.A., Moore, T.J., Johnson, C.C. and Roehrig, G.H., Integrated STEM Education, in *STEM Road Map: A Framework for Integrated STEM Education*, C.C. Johnson, E.E. Peters-Burton and T.J. Moore Ed. 2015, pp. 23-37. Taylor & Francis.
4. Bucciarelli, L., *Engineering Philosophy*. 2003, Delft, The Netherlands: DUP Satellite Press.
5. Coghlan, D. and Brydon-Miller, M., *The Sage Encyclopedia of Action Research*. 2014, Thousand Oaks, CA: SAGE.
6. Crismond, D.P. and Adams, R.S., The informed design teaching and learning matrix. *Journal of Engineering Education,* 2012, 101(4): 738-797.
7. Doppelt, Y., Assessing creative thinking in design-based learning. *International Journal of Technology and Design Education,* 2009, 19: 55-65. https://doi.org/10.1007/s10798-006-9008-y
8. English, L.D. and King, D.T., STEM learning through engineering design: fourth-grade students' investigations in aerospace. *International Journal of STEM Education,* 2015, 2(14): 1-18. https://doi.org/10.1186/s40594-015-0027-7.
9. English, L.D. King, D. and Smeed, J., Advancing integrated STE learning through engineering design: Sixth-grade students' design and construction of earthquake resistant buildings. *The Journal of Educational Research,* 2017, 110(3): 255-271.
10. Gale, J., Alemdar, M., Lingle, J. and Newton, S., Exploring critical components of an integrated STEM curriculum: An application of the innovation implementation framework. *International Journal of STEM Education,* 2020, 7(5). https://doi.org/10.1186/s40594-020-0204-1
11. Glancy, A.W. and Moore, T.J., Theoretical foundations for effective STEM learning environments. *School of Engineering Education Working Papers*, 2013: Paper 1. http://docs.lib.purdue.edu/enewp/1
12. Hoey, M., *Textual Interaction: An Introduction to Written Discourse Analysis*. 2001, Portland: Psychology Press.
13. Jacobson, C. and Lehrer, R., Teacher appropriation and student learning of geometry through

design. *Journal of Research in Mathematics Education,* 2000, 31(1): 71-88.
14. Jun, S.J., Han, S.K. and Kim, S.H., Effect of design-based learning on improving computational thinking. *Behaviour and Information Technology*, 2017, 36(1): 43-53. https://doi.org/10.1080/0144929X.2016.1188415
15. Kelly, T.R. and Knowles, J.G., A conceptual framework for integrated STEM education. *International Journal of STEM Education,* 2016, 3(11). https://doi.org/10.1186/s40594-016-0046-z
16. Kereluik, K., Mishra, P., Fahnoe, C. and Terry, L., What knowledge is of most worth. *Journal of Digital Learning in Teacher Education,* 2013, 29(4): 127-140. https://doi.org/10.1080/21532974.2013.10784716
17. Kirschner, P.A., Sweller, J. and Clark. R.E., Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, 2006, 41(2): 75-86.
18. Koh, J.Q.D. and Tan, A.-L., Students as pharmaceutical engineers: A biology-centric STEM task. *Teaching science*, 2019, 65(1): 26-32.
19. LaForce, M., Noble, E., King, H. *et al.*, The eight essential elements of inclusive STEM high schools. *International Journal of STEM Education,* 2016, 3(1). https://doi.org/10.1186/s40594-016-0054-z
20. Margot, K.C. and Kettler, T., Teachers' perception of STEM integration and education: a systematic literature review. *International Journal of STEM Education*, 2019, 6(2). https://doi.org/10.1186/s40594-018-0151-2
21. Mayer, R., *Multi-media Learning*. 2001, Cambridge, UK: Cambridge University Press.
22. Mayer, R., Should there be a three-strikes rule against pure discovery learning? The case for guided methods of instruction. *American Psychologist*, 2004, 59: 14–19.
23. Polya, G., *How to Solve It: A New Aspect of Mathematical Method.* 1945, Princeton University Press.
24. Quaye, R.M., *Griffin hospital: Insulin pen misuse could have infected patients with diseases.* Retrived on December 9, 2020 from https://www.nhregister.com/connecticut/article/Griffin-Hospital-Insulin-pen-misuse-could-have-11724933.php
25. Rudner, L.M. and Boston, C., Performance assessment. *ERIC Review*, 1994, 3(1): 2-12.
26. Sweller, J., Evolution of human cognitive architecture. *The psychology of learning and motivation*, 2003, 43: 215–266.
27. Sweller, J., Instructional design consequences of an analogy between evolution by natural selection and human cognitive architecture. *Instructional Science*, 2004, 32: 9–31.
28. Tan, A.-L., Teo, T.W., Choy, B.H. and Ong, Y.S., The S-T-E-M Quartet. *Innovation and Education,* 2019, 1(3): 1-14.
29. Thibaut, L., Ceuppens, S., De Loof, H. *et al.*, Integrated STEM education: A systematic review of instructional practices in secondary education. *European Jourrnal of STEM Education*, 2018, 3(1). https://doi.org/10.20897/ejsteme/85525
30. U.S. Department of Health and Health Sciences, *User-centered Design Basics*. 2006. Retrieved on December 9, 2020 from https://www.usability.gov/what-and-why/user-centered-design.html
31. van Eijk, D., van Kuijk, J., Hoolhorst, F., Kim, C., Harkema, C. and Dorrestojn, S., Design for usability: Practice-oriented research for user-centered product design, in *IEA 2012: 18th World Congress on Ergonomics – Designing a sustainable future*, 2012, 41(1): 1008-1015.

32. Wells, J., PIRPOSAL model of integrative STEM education: Conceptual and pedagogical framework for classroom implementation. *Technology and Engineering Teacher*, 2016, 75(6): 12-19.
33. Winter, E.O., *Some Aspects of Cohesion in Sentence and Clause in Scientific English.* 1968, University College London.
34. Yeager, D.S., Romero, C., Paunesku, D. et al., Using design thinking to improve psychological interventions: The case of the growth mindset during the transition to high school. *Journal of Educational Psychology*, 2016, 108(3): 374–391. https://doi.org/10.1037/edu0000098
35. Zeitz, P., The Art and Craft of Problem Solving. 1999, New York, NY: John Wiley & Sons.
36. Zoltowski, C.B., Oakes, W.C. and Cardella, M.E., Students' ways of experiencing human-centered design. *Journal of Engineering Education*, 2013, 101(1): 25-59. https://doi.org/10.1002/j.2168-9830.2012.tb00040.x