DESIGNING PROBLEM-CENTRIC STEM ACTIVITIES

Abstract - In the 21st century where skills application and knowledge integration are prized, there is strong advocacy to include Science, Technology, Engineering and Mathematics (STEM) education in many education models. The goal of this study is to examine teacher's instructional practice and students' experiences in terms of the questions asked as they engaged in a problem-centric STEM activity. We designed a science and engineering-focused activity on the theme of photosynthesis and agricultural engineering. The first of the three-lesson series was conducted by a science teacher, who had gone through a professional development course on STEM teaching, to a class of 19 secondary-two express students. Data sources include a video of the lesson that was directed at the whole class, a video of a randomly chosen group during group problem-solving, transcripts of the videos, and students' notes. From the transcript, teacher's and student's questions were categorised and tabulated. Findings show that Socratic questioning was most frequently used by the teacher in the problematising phase. Productive questioning and making real-world connections allowed the class to effectively understand the problem. During group-problem solving and the design process, students raised mainly clarification, generic task-procedural and specific task-procedural questions. By looking at students' thought processes, we found evidence of informed design patterns.

Keywords – STEM Education, Problem-Centric, Teacher Questioning and Student Questioning

INTRODUCTION

The learning of integrated Science, Technology, Engineering and Mathematics (STEM) has been touted as a means to provide a competent workforce required for the disruption created by the fourth industrial revolution. As such, there is a push for STEM education to be included more pervasively in education models in recent years (Thibaut et al., 2018). Despite integrated STEM education gaining traction in many countries, there remains a lack of consensus in its definition (Siekmann, 2016), instructional practices (Thibaut et al., 2018), and goals (Brown et al., 2011). Nonetheless, a common character of STEM education used by STEM education researchers is the amalgamation of real-world contexts, challenging problem-solving, teamwork, and constructing multidisciplinary connections, which constitutes deeper learning as explained in Otto et al. (2020). Further, these pedagogical methods match the goals of the Education 4.0 initiative introduced in the recent report by World Economic Forum, where it states that "interactive methods that promote the critical and individual thinking (are) needed in today's innovation-driven economy" (World Economic Forum, 2020). Given the popularity of integrated STEM practices, it is timely to better understand students' STEM learning experiences. In this study, we aim to find out teachers' and students' questions raised as they participate in an integrated STEM task centred on a problem. The research questions are:

1. How types of questions are utilised by teachers as part of their instructional practices during problem-centric STEM lessons?

2. What questions do students raise when they are engaged in integrated STEM problem solving?

The structure of the integrated STEM activity designed for this study was guided by the STEM Quartet instructional framework. The STEM Quartet instructional framework (Tan, Teo, Choy & Ong, 2019) is centered around a complex, persistent and extended problem, and involves vertical learning within a discipline as well as horizontal connections between different disciplines. The intention to develop an engineer's strand of thought amongst students is aligned with the objective of STEM education spelled out in Bryan et al. (2016). Furthermore, the positive correlation between science inquiry and engineering design is explained in Purzer et al. (2015), which mentioned that the two entities both foster "learning by doing". As such, the STEM activity emphasises more on the Science and Engineering aspects.

The STEM activity used in this study focused on photosynthesis and agricultural engineering. The problem presented to students is the issue of food self-sustainability in land-scarce Singapore, to which students are required to tackle by generating agricultural engineering solutions. This topic was chosen as it is relevant to Singaporean students who are familiar with the fact that there is high land competition in the country. It is especially apparent with the panic buying situation in many countries as a result of the COVID-19 pandemic. The proposed problem of food self-sustainability is complex, persistent and extended as it is characterised by having multiple solutions, being able to be applied to different contexts, and is challenging as well as realistic (Tan, Teo, Choy &

Ong, 2019). With the context of limited land space, students are tasked to design a prototype for a new farming system that occupies as little space as possible, is cost-effective, and is not labour-intensive, without compromising the crop yield.

The Informed Design Learning and Teaching Matrix by Crismond and Adams (2012) presents a list of nine informed design patterns: (1) problem framing; (2) doing research; (3) idea fluency; (4) deep drawing and modelling; (5) balance benefits and trade-offs; (6) valid tests and experiments; (7) diagnostic troubleshooting; (8) managed and iterative designing; and (9) reflective design thinking. These behaviours are incorporated with the engineering process as described in English et al. (2016). Hence, we devised the STEM activity to include the stages of problematising, researching, generating plausible solutions, designing by drawing, constructing models, presenting, reviewing, and evaluating the solutions.

USE OF QUESTIONING IN SCIENCE LEARNING

Numerous literatures (e.g., Chin, 2007; Chin & Osborne, 2010; Tan, Lee & Cheah, 2017) emphasised on the indispensable role of student and teacher questioning in learning science as well as in argumentation. Scientific inquiry is a learning model in which students engage in hands-on activities that allows them to construct knowledge through learning by doing (Satchwell & Loepp, 2002). Questioning plays a crucial part in science discourse and inquiry-based learning (Wells, 2016). Teacher questioning significantly influences students' responses (Lee & Irving, 2018), while student questioning facilitates teaching and learning, and guides students' thinking (Kuhn, 2009).

Studies have shown that effective teachers demonstrate purposeful science discourse skills in teaching inquiry skills and in helping students to construct scientific knowledge (Gillies & Baffour, 2017; Hardy et al., 2010). Dialogic communication and having more student-teacher interactions in classrooms have long been proven to be more effective teaching methods over the conventional monologic top-down delivery. Teachers' classroom discourse can be analysed through teacher questioning which determines the structure of classroom talk, scaffolds discussion and guides students' cognitive process (Chin, 2007). Hardy et al. (2010) also emphasised the strong impact that teacher prompts place on student conceptual understanding and argumentation skills. Therefore, by analysing teachers' questions, we can study how class discussions are initiated (Wells, 2016) as well as how it affects students' argumentation pattern (Webb, Nemer & Ing, 2006).

Student questioning has implications in both teaching and learning of science (Chin & Osborne, 2008). Asking questions helps students to evaluate their understanding (Chin, 2006) and facilitate knowledge construction (Wells, 2016). As part of social negotiation, student questioning during group activities provide insights on students' thought process and are evidence for the presence of higher-order thinking (Tan, Lee & Cheah, 2017). Examining students' arguments show how students make use of evidence and conceptual understanding in questioning assumptions, warranting their ideas and persuading their ideas to their peers, hence displaying critical thinking (Duschl, 2008). Hence, the role of student questioning in inquiry-based learning is pivotal in that it helps students to steer their learning, and self-review their understanding. For teachers, student questioning can be used as diagnostic tools to assess student understanding or lack thereof. Student questioning can be harnessed to foster productive and purposeful social negotiation pattern to allow for meaningful collaborative and cooperative learning to take place (Chin & Brown, 2002) as well as generate epistemic understanding of an argument (Nam & Chen, 2017).

MATERIALS AND METHODS

The specific task of the STEM activity is to design a new farming system that can maximise crop yield within the context of land scarcity in Singapore to solve the problem of food self-sustainability. In this section, we present the overall unit plan of the three-lesson activity and the analysis of the first lesson.

Lesson one included the teacher and students describing the context in which the problem is located. Thereafter, students gathered into groups of four to research on high-tech farming methods, ask questions (e.g., task-procedural and clarification questions), present their ideas and decide on their new farming system collectively as a group. Students also started designing their prototype by drawing on their activity handout. In lesson two, students built a model of their prototype using basic materials such as ice-cream sticks, metal wires, straws, wooden sticks etc. Finally, students presented their prototype drawing and model in lesson three. During peer presentations, students provided critiques to the ideas presented by their peers. Following that, each group reviewed the pros and cons of their prototypes to assess the feasibility of their prototypes.

DATA COLLECTION

Nineteen secondary-two students from the express stream and Ally (pseudonym), a science teacher from the same school, participated in this study. While the students did not have any formal lessons on photosynthesis, we assumed that they know plants require sunlight, carbon dioxide and water to photosynthesise, as this concept was taught in primary schools. Prior to teaching the class, Ally had undergone a two-hour professional development session on teaching integrated STEM lessons. During the session, Ally was presented with the resources needed for the STEM activity and she also had the chance to clear her doubts with the researchers. This professional development session was needful to help to overcome the issue of the teacher feeling underprepared in STEM classrooms (El-Deghaidy & Mansour, 2015).

The first lesson was implemented during curriculum time with three researchers as observers. To record the whole class setting, a video camera was set up at the back of the classroom and was directed towards the front of the classroom, capturing the teacher, students and the projected PowerPoint slides. During group discussions, a group of students was randomly chosen, and the students' discussion was video recorded. Data sources for this study included the videos and notes that the students had jotted down during their discussion to consolidate their findings. The videos were observed for the teacher's actions including teacher-student interactions. The videos were also transcribed verbatim to analyse the teacher and student talk. The students' notes served as student artefacts that provided insights into the students' research and thought processes.

DATA ANALYSIS

The goals of the data analysis were to examine (1) the questions used by Ally to achieve the essential features of an integrated STEM classroom, and (2) the students' social negotiation pattern during a group problem-solving activity. In the analysis of the discourse, the various phases of the lesson were first identified, to note down the duration of each phase and the actions of Ally and the students. Next, key discussions and questions asked in each phase were examined and categorised.

To achieve the first analysis goal, the essential features of an integrated STEM classroom were mapped out based on the framework for essential features of STEM learning by Toh et al. (under preparation). Table 1 summarised these features. Ally's questions that were both directed at the class and at the group were identified from the transcript. The questions were then categorised based on the different productive questioning approaches as defined by Chin (2007). We focused on examining how Ally adopted pumping, constructive challenge and framing questions (Table 2) to demonstrate the essential features of STEM. The remaining questions, such as clarification questions were categorised as "others".

TABLE 1: Essential features of an integrated STEM classroom (Toh et al., under preparation).

Essential Feature	Competencies
Problematising	The teacher is able to: • Clearly set the context in which the problem is located. • Clearly present the proposed problem to the students, showing how the problem is complex, persistent and extended. • Make or facilitate the formation of explicit links that connect the problem to the context.
Group Problem-Solving	• The teacher provides students with an opportunity to work in groups of two or more students to think of plausible solution(s). • Group members are assigned clear roles by the teacher or by themselves. • Sufficient and suitable facilitation is given by the teacher.
Design Process	• Students are given an opportunity to develop their ideas through creating a prototype in various ways such as drawings, building a model, etc. • An opportunity is given to students for review and evaluation of the prototype's feasibility, pros and cons.
Interdisciplinary Solutions	• Plausible solution(s) generated by students assimilates two or more STEM disciplines. • Clear connections between the solution(s) and the context are made. • Epistemic links between the STEM disciplines integrated in the solution(s) are drawn. • Clear explanations of how the solution(s) solves the problem in the context are provided.

TABLE 2: Description of the types of teacher's questions analysed in this report (Chin, 2007).

Type of Question	Features	Purpose
Pumping	Direct requests made to a prior student's utterance for elaboration on the proposed idea.	To elicit more information from students and encourage them to develop their ideas further.
Constructive Challenge	A challenge to a prior utterance to generate reflective thinking, especially when the student's utterance is incorrect or inaccurate.	To encourage students to re-think their ideas or self-correct their response.
Framing	Overarching questions to structure or outline a new discussion.	To initiate a discussion and stimulate generative thinking amongst students.
Others	Task-relevant questions that do not classify as framing or pumping or constructive challenge question.	–

To examine students' social negotiation pattern, we analysed students' questioning during the group discussion. We focused on three types of questions that were common in the students' talk (i.e., generic task-procedural questions, specific task-procedural questions, and clarification questions). Questions that do not fall into any of the three categories were classified as miscellaneous. Table 3 summarised the various question types. To strengthen the analysis, student's responses and the notes that they have written during their discussion were also studied.

TABLE 3: Description of the types of student's questions analysed in this report.

Type of Question	**Features**	**Purpose**
Generic Task-Procedural	No evidence or scientific concepts are used in the questioning.	To seek for the next step or action needed to carry on with the task.
Specific Task-Procedural	Evidence, scientific concepts, or context are included in the questioning.	To ask for reasoning or explanation of an aspect needed to proceed with the task.
Clarification	To ask about information that are ambiguous or missing to the questioner.	To seek for confirmation or consolidation of information.
Miscellaneous	All other task-relevant questions that do not classify as task-procedural or clarification	–

RESULTS AND DISCUSSION

The 40-minute lesson had three phases (1) problematising, (2) group problem-solving, and (3) design process. In the problematising phase, there was an eight-minute teacher-facilitated discussion on the problem of food self-sustainability. Ally also led the students in co-constructing the implications that land scarcity has on the problem of food production and food sustainability. The discussion between limited land (context) and sustained food production (problem) presented an opportunity for students to make the connections between the context and the problem. Subsequently, the students proceeded to generate plausible solutions in groups of four (group problem-solving). In their groups, students researched on high-tech farming methods, asked questions, and engaged in argumentative discussions to present their ideas, ultimately deciding on their new farming system collectively. The process took about 19 minutes. During this group discussion period, the teacher took the role of a facilitator, guiding the groups of students by answering questions when necessary. Upon confirming their new farming system, the students entered the phase of design process by drawing the design of the system on their handout.

TEACHER QUESTIONING

In the eight-minute problematising phase, the level of interaction between the teacher and students was at the class level before students were divided into their respective groups for group problem-solving and the design process. In the examples that follows, Ally is represented by "T"; a single unidentifiable student speaker is denoted by "S"; multiple unidentifiable student voices are denoted by "SS"; and "xxx" represents inaudible utterance.

TABLE 4: Analysis of teacher's questions.

Type of question	Number of teacher's questions	Proportion of total questions (%)
Pumping	26	68.4
Constructive challenge	4	10.5
Framing	5	13.2
Others	3	7.90
Total	**38**	**100**

Ally's choice of using framing questions to outline a discussion (Excerpt 1) rather than directly delivering the content of the topic is strategic in activating generative thinking in students. The framing questions were also presented on PowerPoint slides, acting as objects of inquiry for students to concentrate on and refer to as the discussion followed (Chin, 2007). Socratic questioning is a questioning technique to tease out more information from students by using a series of prompts (Paul & Elder, 2007). Among the 38 questions, 35 were asked in the problematising phase and the remaining three questions were directed at a group during group problem-solving. Pumping is the main strategy used by Ally to contextualise the problem, with 68.4% of teacher's questions being pumps (Table 4). After establishing the fact that Singapore has insufficient land for open field farming, Ally went on to tease out information from students about Singapore's food supply sources and referred to the panic buying situation (Excerpt 1). With that, Ally managed to incorporate current real-world situation into the classroom talk, making the problem relatable to the students. Ally continued to co-construct knowledge about the pertinence of land scarcity on food self-sustainability with the students using Socratic questioning. Parallel to STEM instructional practices as delineated by Guzey et al. (2016) and Brown et al. (2011), Ally demonstrated the first essential feature of STEM (i.e., problematising) by engaging the class in a dialogic discussion that involved making real-world connections. Hence, Ally had performed strategic questioning approaches which helped to "maintain a rigorous, coherent, engaging, and equitable discussion" (Michaels & O'Connor, 2012, p. 4).

Excerpt 1. Where do we get our food supplies?

	Type of teacher's question
T: *However, we are all human beings and we need to eat right?*	Framing
T: *So, where do we get our food supplies?*	Framing
SS: Import.	
T: Okay, we import from other countries. *Can you name me some of the countries we get our food from?*	Pumping
SS: Malaysia. Vietnam. USA. China. India. Thailand.	
T: I think you are more aware now with the recent series of panic buying occurring in Singapore. *Why, why was there panic buying?*	Pumping
T: (gesturing at a student) *Can you share with us?*	Pumping
S: We're scared that there will be a lockdown in Singapore and there will be xxx	
T: We are afraid that there is a lockdown in SG because of the COVID-19 situation and there can be no food coming to Singapore.	

Instances where students had made an inaccurate utterance, Ally responded with a constructive challenge instead of directly correcting their answer. Constructive challenge questions took up only 10.5% of all questions, showing that the students were able to comprehend the lesson well, showed little misconceptions, or were too shy to voice their ideas. Excerpt 2 shows how Ally effectively used constructive challenge and pumping to elicit the idea of vertical farming from the students. Once again, we see Ally reiterating student's responses, this time posing an additional question to challenge the claim. "Revoicing" (Chapin, O'Connor & Anderson, 2009) students' responses to share their ideas to the class, hence transforming an individual's knowledge into shared common knowledge. Next, Ally posed a constructive challenge to the claim of farming in Singapore (Excerpt 2), generating reflective thinking in not just the student who answered, but in the rest of the class as well. This led to more responses from the class, ultimately eliciting "vertical farming" as a solution. Therefore, Ally had demonstrated purposeful teacher questioning which "followed upon a preceding student contribution in a productive way" (Chin, 2007).

Excerpt 2. How can we grow food without space?

	Type of teacher's question
T: *How can we solve this problem of food supply in Singapore? Limited food supplies, what can we do?*	Pumping
S: xxx	
T: (gesturing to a student) *What did you say?*	Others
S: We farm by ourselves	
T: We farm by ourselves. We grow crops ourselves. *But no space what, what to do? So how can we grow food without space?*	Constructive Challenge
SS: xxx	
T: *Your friend is doing this (gesturing a vertical structure with both hands) what is this?*	Pumping
SS: Vertical farming	

Therefore, the findings had exhibited how purposeful teacher questioning and using real-world linkages are important in facilitating students' understanding of the problem by strongly influencing students' responses (Lee & Irving, 2018). As the lesson progressed to group problem-solving, Ally assigned roles to each student in the groups – a notetaker, a researcher and two article-readers. Students were in charge of their own group's discussion where they raised questions and negotiated their ideas with their groupmates while Ally moved between groups to scaffold the discussions when necessary, characterising this as cooperative learning (Thibaut et al., 2018). Creating the chance for group discussions presents a stage for students to communicate STEM concepts, construct multidisciplinary connections and solve problems by working with one another (Stohlmann et al., 2011).

STUDENT QUESTIONING

As there are multiple aspects to the overarching problem, ensuing multiple solutions, students were given the autonomy to research on specific areas of focus, discuss and work in groups to come up with a new farming system design as a plausible solution to ensuring food self-sustainability by maximising crop yield in a limited area of land. We analysed the student's questions raised in group problem-solving and design process respectively. The number and proportion of student's questions are tabulated in Table 5. In the excerpts that follow, identifiable group members are represented by "G1" to "G4".

TABLE 5: Type, number and proportion of students' questions.

Type of question	Number of student's questions	Proportion of total questions (%)
Clarification	24	38.7
Generic Task-Procedural	12	19.4
Specific Task-Procedural	14	22.6
Miscellaneous	12	19.4
Total	**62**	**100**

Clarification questions were the most prevalent among student's questions, taking up to 38.7% (Table 5). When clarifying, students often rephrased the previous utterance (Tan, Lee & Cheah, 2017) or simply probed *"what is that?"* when referring to the sketch of the farming system. We noticed that two-thirds of the clarification questions were made during the design process when group members probed their peer as he drew the design of their aquaponics system. Some clarifications made were *"Oh, you mean the fishes here?", "Is that actually the water pump?"* and *"Then how do they (crops) get the water?"*. Excerpt 3 shows an exchange involving clarification questions where two members discussed about the type of plants that can be planted using rooftop greenery as a farming method. It shows G3 seeking confirmation to register new information about the rooftop farming method that they have researched on. The action of clarifying benefits the group in achieving a common understanding, eliminating confusion and it also displays the thought processes of the students (Tan, Lee & Cheah, 2017).

Excerpt 3. You need to water it?

	Type of student's question
G3: *So, it depends on the rain?*	Clarification
G1: No, it doesn't really depend on the rain, cause it's drought tolerant. Like cactus lah.	
G3: *Oh, like do you need to water it?*	Clarification
G1: I mean ya of course. Plants need water.	
G3: *So, like if you water it then why must it be drought-tolerant?*	Clarification
G1: It's the it's the plant's characteristic.	

Task-procedural questions can be generic or specific depending on whether the student is asking *"what should we do?"* in general or if the question is targeted at a particular information. Specific task-procedural questions often include conceptual knowledge or evidence in the question stem. For instance, one student first asked generically, *"what are we going to do?"* before rephrasing his question to be more targeted, *"what other types of agriculture are there in Singapore?"* From here, it is observed that generic task-procedural questions may take the form of figuring out loud, showing the student's wonderment before realising the task that needs to be performed or arriving at a necessary conclusion. To add on, Excerpt 4 illustrates how students utilised specific task-procedural questions to weigh the benefits and limitations of the farming method that they have found. Thus, apart from providing insights about students' thinking processes, task-procedural questions also illustrated evidence of informed design such as balancing pros and cons (Purzer et al., 2015).

Excerpt 4. Just one?

	Type of student's question
G1: *So, we'll use this as the main. And then which one do you want to use? Rooftop greenery or hydroponics?*	Specific task-procedural
G1: You can take two if you want	
G3: Nah, I don't think we should take two, just one sub is enough.	
G1: *Just one?*	Specific task-procedural
G3: Ya.	
G1: *Why?*	Specific task-procedural
G3: Taking two is going to get confusing.	
G1: You can use hydroponics also you know. *Because if the water isn't enough for the fishes, how is it going to supply back to the plant?*	Specific task-procedural

From the video, we also observed several times when the students were distracted and went off-topic. During those times, their attention was brought back to the task when a group member (G1) prompted for their concentration. It should also be remarked that G1 led the discussion, drew the design and appeared to be the most on-task. Since it would be difficult for the teacher to manage all groups simultaneously, a suggestion would be to assign a group leader in each group who will take charge of organising the team, structuring discussions and ensuring that the members are on-task. This would also make group problem-solving more student-centred, as heavier responsibilities are placed on the students. Classroom management issues could also be reduced. Another limitation was the fact that we were unable to fully implement the integrated STEM activity. Nonetheless, the findings from the first lesson had provided evidence that warrants the advantages of integrating problem-solving and engineering design into science learning (Purzer et al., 2015), resulting in meaningful STEM education.

In conclusion, by analysing the teacher's questions, we identified Ally's appropriate employment of framing questions and extensive use of Socratic questioning in facilitating students' understanding of the problem. From the student's questions, we noticed how students used clarification and task-procedural questions to foster discussion, guide their understanding and construct knowledge. These are parallel to the functions of student's questioning as outlined by Chin and Osborne (2008). This study can add to the foundation of research on problem-centric STEM activities. Should there be further research, obtaining a full data set would be greatly beneficial in offering deeper insights about students' experiences when engaged in problem-centric integrated STEM activities.

ACKNOWLEDGEMENT

X 4404 words

REFERENCES

Brown, R., Brown, J., Reardon, K., & Merrill, C. (2011). Understanding STEM: Current perceptions. *Technology and Engineering Teacher, 70*(6), 5–9.

Bryan, L. A., Moore, T. J., Johnson, C. C., & Roehring, G. H. (2016). Integrated STEM education. In C. C. Johnson, E. E. Peters-Burton, & T. J. Moore (Eds.), *STEM Road Map: A framework for integrated STEM education* (pp. 23–38). New York, USA: Routledge.

Chapin, S. H., O'Connor, C., & Anderson, N. C. (2009). *Classroom discussions: Using math talk to help students learn, Grades K-6*. Math Solutions.

Chin, C., & Brown, D. E. (2002). Student-generated questions: A meaningful aspect of learning in science. *International Journal of Science Education*, *24*(5), 521-549.

Chin, C. (2006). Using self-questioning to promote pupils' process skills thinking. *School Science Review, 87(*321), 113–122.

Chin, C. (2007). Teacher questioning in science classrooms: Approaches that stimulate productive thinking. *Journal of Research in Science Teaching, 44*(6), 815–843.

Chin, C., & Osborne, J. (2008) Students' questions: A potential resource for teaching and learning science. *Studies in Science Education, 44*(1), 1–39.

Chin, C., & Osborne, J. (2010) Supporting argumentation through students' questions: Case studies in science classrooms. *The Journal of the Learning Sciences, 19*(2), 230-284.

Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education, 101*(4), 738–797.

Duschl, R. (2008). Quality argumentation and epistemic criteria. In S. Erduran & M. Aleixandre (Eds.), *Argumentation in Science Education:* (pp. 159-175). Dordrecht, the Netherlands: Springer.

El-Deghaidy, H. & Mansour, N. (2015). Science teachers' perceptions of STEM education: Possibilities and challenges. *International Journal of Learning and Teaching, 1*(1), 51-54.

English, L. D., King, D., & Smeed, J. (2016). Advancing integrated STEM learning through engineering design: Sixth-grade students' design and construction of earthquake resistant buildings. *The Journal of Educational Research, 110*(3), 255–271.

Gillies, R. M., & Baffour, B. (2017). The effects of teacher-introduced multimodal representations and discourse on students' task engagement and scientific language during cooperative, inquiry-based science. *Instructional Science*, *45*(4), 493-513.

Guzey, S. S., Moore, T. J. & Harwell, M. (2016). Building up STEM: An analysis of teacher-developed engineering design-based STEM integration curricular materials. *Journal of Pre-College Engineering Education Research, 6*(1), 1129.

Hardy, I., Kloetzer, B., Moeller, K., & Sodian, B. (2010). The analysis of classroom discourse: Elementary school science curricula advancing reasoning with evidence. *Educational Assessment*, *15*(3-4), 197-221.

Kuhn, D. (2009). Do students need to be taught how to reason? *Educational Research Review, 4*(1), 1-6.

Lee, S. C., & Irving, K. E. (2018). Development of Two-Dimensional Classroom Discourse Analysis Tool (CDAT): Scientific reasoning and dialog patterns in the secondary science classes. *International journal of STEM education*, *5*(1), 5.

Michaels, S., & O'Connor, C. (2012). Talk science primer. *Cambridge, MA: TERC*.

Nam, Y., & Chen, Y.-C. (2017). Promoting argumentative practice in socio-scientific issues through a science inquiry activity. *EURASIA Journal of Mathematics, Science and Technology Education, 13*(7), 3431–3461.

Otto, S., Körner, F., Marschke, B. A., Merten, M. J., Brandt, S., Sotiriou, S., & Bogner, F. X. (2020). Deeper learning as integrated knowledge and fascination for Science. *International Journal of Science Education*, 1(28).

Paul, R., & Elder, L. (2007). Critical thinking: The art of Socratic questioning. *Journal of Developmental Education, 31*(1), 36-37.

Purzer, Ş., Goldstein, M. H., Adams, R. S., Xie, C., & Nourian, S. (2015). An exploratory study of informed engineering design behaviors associated with scientific explanations. *International Journal of STEM Education*, *2*(1), 9.

Satchwell, R. E., & Loepp, F. L. (2002). Designing and Implementing an Integrated Mathematics, Science, and Technology Curriculum for the Middle School. *Journal of Industrial Teacher Education*, *39*(3), 41-66.

Siekmann, G. (2016). What Is STEM? The Need for Unpacking Its Definitions and Applications. *National Centre for Vocational Education Research (NCVER)*.

Stohlmann, M., Moore, T. J., McClelland, J., & Roehrig, G. H. (2011). Impressions of a middle grades STEM integration program: Educators share lessons learned from the implementation of a middle grades STEM curriculum model. *Middle School Journal, 1,* 32-40.

Tan, A.-L., Lee, P. P. F., & Cheah, Y. H. (2017) Educating science teachers in the twenty-first century: Implications for pre-service teacher education. *Asia Pacific Journal of Education,* 37(4), 453-471.

Tan, A.-L., Teo, T. W., Choy, B. H., & Ong, Y. S. (2019). The S-T-E-M Quartet. *Innovation and Education*, *1*(3).

Thibaut, L., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A., Boeve-de Pauw, J., … Depaepe, F. (2018). Integrated stem education: a systematic review of instructional practices in secondary education. *European Journal of STEM Education, 3*(1), 02.

Toh, K. W. C., Tan, A. –L., Ong, Y.-S., Ng, Y. S., Natarajan, U., Koh, H. D. E., Lau, S. X. R., & Ang, H. Y. (under preparation). Characterising integrated STEM classrooms: Essential features of STEM learning.

Webb, N. M., Nemer, K. M., & Ing, M. (2006). Small-group reflections: Parallels between teacher discourse and student behavior in peer-directed groups. *The Journal of the Learning Sciences*, *15*(1), 63-119.

Wells, J. G. (2016). PIRPOSAL model of integrative STEM education: Conceptual and pedagogical framework for classroom implementation. *Technology and Engineering Teacher, 75*(6), 12-19.

World Economic Forum (2020). Schools of the future: Defining new models of education for the fourth industrial revolution.