Title	Developing an integrated STEM classroom observation protocol using the productive disciplinary engagement framework
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Developing an Integrated STEM Classroom Observation Protocol Using the Productive Disciplinary Engagement Framework

Abstract

STEM education and research has gained popularity internationally over the last decade. However, there is a lack in specifications in existing K-12 STEM classroom observation protocols of how features of an integrated STEM experience/lesson would lead to desired outcomes and how those outcomes should be measured. To bridge this gap, we propose the development of a new integrated STEM classroom observation protocol (iSTEM protocol). This article describes the ongoing development work of the iSTEM protocol, which features two creative attempts. Firstly, the productive disciplinary engagement framework is adapted to design a classroom observation protocol that provides a coherent frame of design principles to be met to achieve desired 3-dimensional pedagogical outcomes. Secondly, *interdisciplinarity* of student engagement was interpreted in terms of the extent to which students take a systematic and disciplinary-based approach to make and justify decisions during STEM problem-solving. The iSTEM protocol comprises 15 items (4-point scale) rated holistically for the extents to which evidence was found in the observed lesson for (1) the 3-dimensional pedagogical outcomes of productive interdisciplinary engagement (five items) and (2) problematising, resources, authority, and accountability design principles (10 items). The accompanying iSTEM profile visually represents and communicates the strengths and inadequacies in design principles, thus providing explanations for extents of students' productive interdisciplinary engagement. The iSTEM protocol will contribute as a research tool for STEM education researchers and as a pedagogical guide for STEM classroom teachers to improve their design of STEM learning experiences.

Keywords: interdisciplinary; observation protocol; productive disciplinary engagement; STEM education

Introduction

STEM education and research has gained popularity internationally over the last decade (Li et al., 2020). While initially US-based, STEM education has gained worldwide interest, including among Asian economies (Author, 2021) and Australasia (Murphy et al., 2019; Papua New Guinea [PNG] Education News, 2022). A review of US-based STEM K-12 education programmes noted inadequate specifications of how features of an integrated STEM experience/lesson would lead to desired outcomes and how those outcomes should be measured (National Research Council [NRC], 2014), a problem also encountered in efforts to promote STEM education in Singapore. This problem is partly contributed by the lack of consensus on what counts as STEM education, what STEM integration means (English, 2016; Kelley & Knowles, 2016; NRC, 2014), and what STEM education outcomes are worthy of pursuit.

Observational tools such as a STEM classroom observation protocol present a viable way to provide guidance on what makes a “good” integrated STEM experience for STEM education stakeholders, including researchers, teachers, teacher educators, curriculum developers, and policymakers (Dare et al., 2021). However, our literature search for existing K-12 integrated STEM (rather than monodisciplines STEM) classroom observation protocols (Dare et al., 2021; Peterman et al., 2017; Wheeler et al., 2019) revealed that none articulated a set of design principles/features with corresponding pedagogical outcomes. To bridge this gap, we propose a new integrated STEM classroom observation protocol (iSTEM protocol) informed by the productive disciplinary engagement (PDE) framework (Engle, 2012; Engle & Conant, 2002). Two novel features of the iSTEM protocol are highlighted. Firstly, items were construced based on the PDE framework comprising four design principles–problematising, resources, authority, and accountability–theorised to foster the three-dimensional student outcomes of engagement, interdisciplinarity (modified from disciplinarity), and productivity. Secondly, interdisciplinarity of students' engagement in STEM problem-solving is interpreted as the extent to which students take a systematic and disciplinary-based approach towards decision-making. In this paper, we report on the design considerations and challenges in ensuring the validity, reliability, and usability of the iSTEM protocol.

Literature Review

Defining STEM Integration

Drawing upon definitions of multi-, inter-, and trans-disciplinary proposed by STEM educators (Vasquez et al., 2013) and STEM professionals (Choi & Pak, 2006), the iSTEM protocol focuses on STEM integration at the *interdisciplinary* level. That is, students apply concepts, skills, and practices from two or more STEM disciplines to solve a real-world problem by interacting between disciplines and blurring disciplinary boundaries such that the problem cannot be easily categorised as a science, technology, engineering, or mathematics problem nor can the solution be sought through a single, disciplinary approach. While Vasquez et al. (2013) considered students working on real-world problems/projects by applying knowledge and skills from two or more disciplines as sufficient conditions for transdisciplinary integration, we interpret transdisciplinarity as involving "a common perspective that 'transcends' those that are standard in the two disciplines" (Choi & Pak, 2006, p.355). Our experiences as K-12 educators and researchers suggest it is more likely for schools to achieve interdisciplinary integration, while transdisciplinary integration is more likely at the post-secondary levels as students have greater disciplinary expertise. Hence, our proposed protocol–intended for use in elementary and secondary STEM classrooms–focuses on interdisciplinary integration.

Existing Protocols

Existing STEM classroom observation protocols mostly target postsecondary/college levels and monodisciplines in STEM (for examples, see Anwar & Menekse, 2021). Nevertheless, we identified three integrated STEM observation protocols intended for K-12 classrooms. These protocols–Classroom Observation Protocol for Engineering Design (COPED) by Wheeler et al. (2019), Engineering-Infused Lesson (EIL) Rubric by Peterman et al. (2017), and K-12 STEM Observation Protocol (STEM-OP) by Dare et al. (2021)–are compared as follows and their key features are summarised in Table 1.

Frameworks and STEM integration

All three protocols involved integrated STEM to different extents. COPED and EIL Rubric focused on science and engineering integration; STEM-OP considered integration of all four STEM disciplines generally (see Table 1 for integration-related items). Emphasising engineering design integration in secondary science classrooms, COPED's framework was based on (1) engineering design process components (EDPC: problem, brainstorming, researching, planning, building, testing, evaluating, redesigning, and sharing) and the extents to which processes are teacher-driven versus student-driven, as well as (2) engineering habits of mind (EHOM: creativity, divergent thinking, systems thinking, optimism, collaboration, communication, and attention to ethical considerations). EDPC could be considered an integrated STEM lesson's design features while the EHOM would be the pedagogical outcomes.

EIL Rubric was intended to “help teachers infuse engineering content and activities into their [science] lessons” (Peterman et al., 2017, p.1916). EIL Rubric comprises three sections: curriculum materials (i.e., lesson design features reflected in materials, such as alignment with NGSS standards, the nature of the design challenge presented to students, presence of science content, science-engineering connection, and assessment), design-centred pedagogical practices (for implementing design challenges), and engagement with engineering concepts (use of engineering terminologies and making connections to real-world engineering applications). Aligned to its intention, the EIL Rubric framework emphasises design features of an engineering design challenge lesson but does not consider pedagogical outcomes.

STEM-OP was designed based on the characteristics of integrated STEM education as informed by existing literature. These include (according to item names): relating content to students’ lives, contextualizing student learning, developing multiple solutions, cognitive engagement in STEM, integrating STEM content, student agency, student collaboration, evidence-based reasoning, technology practices in STEM, and STEM career awareness. The ensemble of ten characteristics seemed eclectic rather than based on a coherent framework. For example, there is a mixture of STEM lesson design features (e.g., integrating STEM content; technology practices in STEM), possible pedagogical outcomes (e.g., cognitive engagement in STEM; evidence-based reasoning), and emphasis on students’ STEM identify development through “STEM career awareness”.

Types of Items and Nature of Analysis

The three protocols vary in their types of items and how lessons are analysed. For COPED, the observer codes for the presence of EDPC, EHOM, and grouping (whole class, small group or individual) according to what is observed of any student’s action in 2-minute intervals. For example, if one student in a group demonstrated creativity during brainstorming within a 2-minute interval, codes for creativity and brainstorming, and small group will be circled for that interval. Additionally, the observer is requested to write a lesson description for each interval. Post-observation, the observer indicates (based on observation codes) the extent to which each observed EDPC was teacher- versus student-driven on a 4-point ordinal scale. Thus, COPED comprises segmented analysis of EDPC and EHOM and holistic analysis of extents of teacher- versus student-driven EDPC. Conversely, EIL Rubric is used for analysing lesson documents, such as lesson plans, worksheets, and assessments. The observer determines whether a set of lesson documents meets the requirements on a 19-item checklist grouped into three sections as previously described. A section score is generated based on checked items. Section scores are then added to produce a total, holistic score for the set of lesson documents. Finally, STEM-OP comprises 10 items each on a 4-point Likert scale with specific statements for each rating. All but one item focuses on teacher action (exception is Item 9: Technology practices in STEM, which emphasises student action). Thus, the observer scores an observed lesson holistically using STEM-OP.

Reliability and Validity

All three protocols measured reliability by considering inter-rater reliability and utilized either Cohen’s kappa (COPED) or Krippendorff’s alpha (EIL rubric and STEM-OP). For validity, COPED and STEM-OP ensured content validity by seeking STEM-related experts’ opinion while EIL Rubric did not discuss validity considerations. Furthermore, STEM-OP authors argued for the protocol’s credibility and trustworthiness as its items reflected common characteristics of integrated STEM from the literature.

In summary, among the identified K-12 integrated STEM classroom observation protocols, both EIL Rubric and STEM-OP did not include well-defined design features and pedagogical outcomes. While COPED's framework included both, its emphasis on engineering makes it unsuitable for a broader use with integrated STEM lessons. While COPED (and STEM-OP) established reliability and validity to reasonable extents, in terms of usability, COPED's segmented analysis and writing of lesson descriptions at 2-minute intervals seems daunting even for trained researchers. As none of the reviewed protocols met the requirements of 1) including a set of design features and corresponding pedagogical outcomes, and 2) can be easily used to analyse integrated STEM lessons, we were motivated to develop an integrated STEM observation protocol that addressed these gaps.

Table 1

Key Features of Three K-12 Integrated STEM Observation Protocols

Protocol	**EIL Rubric** (Peterman et al., 2017)	**COPED** (Wheeler et al., 2019)	**STEM-OP** (Dare et al., 2021)
Framework	Items in three sections: • Curriculum materials (lesson design features) • Design-centred pedagogical practices • Engaging with engineering concepts	Engineering design process components (EDPC) and extents to which the processes are teacher-driven versus student-driven, as well as engineering habits of mind (EHOM). Extents of science and engineering integration (based on teacher's intention).	Characteristics of integrated STEM education represented by 10 items. Each item represents a characteristic.
STEM Integration	Infusion of engineering content and activities into science lessons	Science and engineering integration (based on teacher's intention)	Items: 5. Integrating STEM Content (students draw upon content from more than one STEM discipline); 8. Evidence-based Reasoning (for claims/design choices), and 9. Technology Practices in STEM (students' use of digital technology to construct a scientific model or design solution)
Type of Items	19 items (checklist)	Codes for presence of EDCM (9), EHOM (7), and grouping based on	10 items; 4-point scale

		any student's observed action, as well as write lesson description for every 2-minute interval. Determine extents of science and engineering integration and extents to which EDPC are teacher-driven versus student-driven, post-observation.	All but one item (Item 9) focuses on teacher action.
Nature of analysis	Holistic: Analyse lesson documents Summary scores per section (based on checked items) + total score	Segmented (2-minute interval) for EDPC and EHOM. Holistic for extent to which design component is teacher-driven vs student-driven.	Holistic No mention of adding up item scores for overall score.
Reliability	Krippendorff's alpha = .74 (n = 16, 3 raters)	Cohen's kappa = .81 (final) (n = 760 coded entries for two 40-minute videos, 2 raters)	Krippendorff's alpha = .580 to .870 (n = 104, 7 raters)
Validity	No mention	Content validity: two cycles of expert panel (engineers, engineering educators, science educators, and instrument development experts) review and revision.	Credibility and trustworthiness: Common characteristics of integrated STEM were based on literature. Face and content validity: items reviewed by 3 STEM education experts.

Methods

We followed the approaches of existing STEM observation protocols (i.e., Dare et al., 2021; Milford & Tippett, 2015; Wainwright et al., 2003; Wheeler et al., 2019) in developing the integrated STEM classroom observation (iSTEM) protocol. Specifically, protocol development involves three phases: 1) preliminary protocol development, 2) iterative pilot testing, protocol review, and revision, and 3) reliability establishment. We unfortunately made limited progress in phase 3 due to COVID-19 related situations. Nevertheless, we provide an overview of the iSTEM protocol and a detailed description of phases 1 and 2.

Preliminary iSTEM Protocol Development

The iSTEM protocol is intended for observation of individual integrated STEM lessons in primary/elementary and secondary classrooms and should meet three criteria: validity, reliability, and ease of use as a research instrument for analysing live integrated STEM lessons. Additionally, protocol items should be framed by a coherent set of design principles and pedagogical outcomes, which we achieved by applying the productive disciplinary engagement (PDE) framework (Engle, 2012; Engle & Conant, 2002). The PDE framework states four design or guiding principles should be fulfilled to foster students' engagement in specific disciplinary practices (e.g., scientific argumentation) in productive ways that demonstrate intellectual progress (i.e., the three-dimensional pedagogical outcomes). Students should be engaged in problems that are meaningful to the disciplinary community (problematising) and be provided resources to help them solve the problems. Students should also be given the authority to propose/construct their own ideas/solutions yet have their ideas/solutions held accountable to themselves (clarity of expressions), peers (especially differing ideas), the teacher, and disciplinary norms.

Productive Interdisciplinary Engagement

~~The PDE framework was interpreted for the iSTEM protocol as follows.~~ We illustrate how we adapted the PDE framework's three-dimensional outcomes and design principles for the iSTEM protocol by using hypothetical examples of the case of students solving the STEM problem of making a pill coating for an oral medication that meets the criteria of durability (dissolving in the stomach after two minutes), cost, and ease of swallowing the pill (henceforth the pill-coating activity). Detailed analysis of the lesson using the iSTEM protocol is discussed subsequently.

For the three-dimensional outcomes, *engagement* refers to the extent to which students are cognitively engaged during a STEM lesson (one item in iSTEM protocol), working as a group (one item) towards solving a STEM problem. Drawing on the ICAP framework (Chi & Wylie, 2014) and Walton's dialogue types (Walton, 1998), students' cognitive engagement is highest when they engage in critical discussion (students build on and challenge ideas with justifications, or discuss/juxtapose multiple ideas), followed by idea-building (students build on ideas without challenging ideas), information-seeking (mainly one student shares ideas while others ask clarifying questions), and the least when they engage in exposition (mainly the teacher or one student shares/elaborates idea). Moreover, students should be working in their groups to demonstrate such cognitive engagement as group work motivates the need for making individuals' thinking visible to peers. Using the case of the pill-coating activity, a group where students mostly work as a group and multiple students put forward and challenge ideas demonstrates high engagement in group work and critical discussion. Conversely, a group where students work individually on different parts of the problem with one student mainly telling others what to do, demonstrates low engagement.

Defining interdisciplinary practice(s) proved challenging as there is no single, consensus definition. Definitions using 21st century skills such as critical thinking, communication, collaboration, and creativity (Partnership for 21st Century Skills, 2015) loses the disciplinary aspect of integrated STEM as such skills could apply to all disciplines, even beyond STEM. Conversely, opting for discipline-specific practices loses the integrative aspect. Hence, we interpreted *interdisciplinarity* of engagement as the extent to which students take a systematic, disciplinary-based approach to make and justify decisions relevant to solving the STEM problem (one item). High interdisciplinarity means students' decisions are based on weighing benefits and trade-offs, evidence (researched/given information or gathered data), and disciplinary reasonings (e.g., scientific/mathematical reasonings) tied to success criteria/solution requirements.

Referencing the pill-coating activity, groups that evaluate all three solution criteria to reason towards an optimised solution based on evidence from scientific inquiry (e.g., testing each ingredient systematically in incremental amounts to determine minimum amounts to meet durability criterion) and mathematical reasoning (e.g., estimate cost of pill coating based on amount and unit cost of each ingredient used) exemplify high interdisciplinarity in decision-making. Groups that randomly select the amounts of each ingredient or do not justify their decision demonstrate low interdisciplinary. We contend that our interpretation of interdisciplinarity considers both the disciplinary aspect (i.e., disciplinary reasonings) and integrative aspect (i.e., decision-making).

Finally, *productivity* refers to the extent to which students make intellectual progress or improvement in their decision/solution within the observed STEM lesson (one item), and the extent to which students' final solution meets the success criteria/solution requirements (one item). In the pill-coating problem, a group demonstrates high productivity if the students reach a new/improved solution that addresses an issue or meets more success criteria/solution constraints compared to their previous solution by the end of the observed lesson. However, a group demonstrates low productivity if the students do not reach a required decision/solution and no issues with their proposed decision/solution are identified by the end of the lesson. Students' final solution indicates high productivity in product quality if it meets all success criteria and satisfies all constraints. Conversely, a final solution indicates low productivity if it does not satisfy any criteria/constraints.

Our interpretation of *productive interdisciplinary engagement* (PIE) reflects our belief that fostering students' abilities to critically engage in systematic, disciplinary-based decision-making to achieve improved decision/solution to a STEM problem is a worthy goal of integrated

STEM education (Sutaphan & Yuenyong, 2019). This echoes Bybee's (2013) view that STEM literacy, which includes using STEM knowledge, skills, attitudes, and values to solve real-life problems as responsible and reflective citizens, should be the goal of STEM education.

Turning to the four design principles, *problematising* considers the extent to which the nature of the problem taken up by students is a meaningful problem for the students and STEM communities (one item). A meaningful STEM problem is complex (requires concepts/skills from more than one STEM discipline to solve), authentic (relevant to students' lives/real-life), open-ended (has more than one possible solution), extended (requires prolonged working on the problem and cannot be solved by simple search for solution, e.g., via the Internet), and persistent (occurs in multiple contexts; not a once-off problem or problem that only exists in textbooks) (Authors, 2019). The pill-coating activity meets the problematising design principle to a high extent. It is complex as students require scientific inquiry and mathematical reasoning, as described under high interdisciplinarity, to optimise their solution through an iterative engineering design process. It is authentic as the production of pill coating for oral medication is real-life problem. The problem is open-ended as more than one optimal pill-coating design could exist, and it is extended as students cannot simply search for an existing answer but must work over an extended duration to solve the problem.

Problematising should be balanced by *resources*: the extents to which material resources (one item), support from teacher and/or scaffolding (one item) and instructional time (one item) are provided to facilitate students in solving the STEM problem. The pill-coating activity meets the resources design principle to a large extent if (1) students are given all the necessary materials and equipment to produce and test their pill coating, (2) students are provided a handout with adequate scaffolds, such as tables for recording data and prompts for students' justification of their final solution, and their teacher engages in group discussions to support group decision-making, and (3) sufficient instructional time is planned for students to produce and share their final solution. In contrast, the activity design meets resources to a low extent if students have to source for their own materials and equipment, are not provided any assistance via a handout or the teacher, and are given little time to work on the problem.

Authority depicts the extent to which students are given epistemic authority to construct their solution to the STEM problem (one item) with minimal teacher modification (one item) and to determine success criteria/solution requirements (one item). The pill-coating activity satisfies the authority design principle to a high extent if (1) students get to propose their own ideas that are acknowledged by peers for discussion, (2) the teacher critiques or highlights good points about their idea/solution without suggesting what to change, and (3) students have the opportunity to propose additional success criteria with justifications. The activity meets authority to a low extent if students do not propose their own ideas but merely follow instructions to complete the activity, and students accept the criteria given by the teacher.

Authority should be balanced by *accountability*: the extent to which students' ideas/actions are held accountable to STEM disciplinary concepts and practices through critiques (one item) by peers/teacher (one item), and through success criteria/solution requirements (one item). Examples of disciplinary concepts include mathematically/scientifically accurate concepts/facts; examples of disciplinary practices include fair test, appropriate analysis, and 2D/3D sketch/drawing norms. The pill coating activity meets the accountability design principle to a large extent if (1) critiques of a group's ideas/solution are made by the teacher and peers beyond the group, (2) multiple critique instances involve holding ideas/solution accountable to the soundness of STEM disciplinary concepts or practices (including satisfying criteria/constraints), and (3) the criteria/constraints involve sound concepts/practices from two or more STEM disciplines. Conversely, the activity meets the accountability principle to a low extent if there are no opportunities for critique beyond respective groups, there are few critique instances during group discussion, and success criteria are not present or not made explicit to students.

Characteristics of STEM Lessons Captured in iSTEM Protocol

An engineering or technological design context, such as a design challenge, has been recognised as a productive and common context for STEM integration (English, 2016; NRC, 2014). Thus, iSTEM protocol can be used with a lesson in an integrated STEM unit of work or activity that involves a design challenge where students draw upon their conceptual knowledge, procedural skills/methods, and/or practices from at least two STEM disciplines to solve a real-life problem and design its solution through design processes. The solution could take the form of a design sketch/drawing, a prototype or scaled/working model, or the actual object as the solution. We identified eight relevant design processes from the engineering practices and design thinking literature (Crismond & Adams, 2012; Cunningham et al., 2020; d.school at Stanford University, 2018; Wheeler et al., 2019), which we labelled as STEM tasks and categorised into three STEM phases. The *problem definition* phase involves the tasks of context introduction and problem definition (including identification of success criteria/solution requirements). The *research* phase focuses on gathering information or data to inform the solution design and includes search (for existing information) and investigate (e.g., carry out investigations to gather data). The *development* phase includes tasks relevant to the solution development: generate (proposing ideas/representations of intended solution), concretize/make (i.e., create/revise a form of the solution), test (of the solution), and feedback (i.e., present the solution to peers/teacher for feedback and/or reflect on feedback.

Iterative Pilot Testing, Review and Revision

The initial iSTEM protocol, comprising 13 items for PIE outcomes and design principles rated on a 4-point scale, was conceptualised by the first author. It was then reviewed by the research team including science education and design and technology education experts (other authors). The expert review included analysing a video-recorded 2-hour STEM lesson using the protocol. A key issue deliberated by the team was whether the analysis should be holistic or segmented. We initially trialled a version of the protocol with segmented analysis. A STEM lesson was analysed for the extents to which the PIE design principles and pedagogical outcomes were observed in every 15-minute interval. However, we encountered the challenge that the imposed time interval could not accommodate the natural segmentation of STEM tasks as a STEM lesson progresses, and the nature of the STEM task could impact extents of PIE design principles and pedagogical outcomes. While a shorter time interval might circumvent this issue (e.g., Wheeler et al., 2019), we contend this would compromise the protocol's ease of use as judgements of the PIE outcomes and design principles items within such short time intervals are cognitively demanding. We eventually decided on a holistic analytical approach whereby ratings are indicated for the whole observed lesson. The protocol requires the observer to write descriptive notes on the lesson, which serve as evidence to support item ratings. This enables the observer to focus on observing and documenting features during the lesson, then deliberate on the relevant evidence that support the ratings post-observation. The latter is important if multiple observers are involved and consensus ratings need to be reached, and when communicating the ratings to the teachers as feedback.

The holistic iSTEM protocol was tested by two of the authors with ~~two~~ STEM lesson recordings ~~(one~~ at primary and ~~one at~~ secondary levels~~,)~~ and revised following discussions with the research team to strengthen and clarify the construct definitions. Based on contrasting features of the observed lessons, one design principle item–resources: time–was added to reflect the need for-provision of adequate time for students to work on STEM tasks and one outcome item–engagement: group work–was added to consider the extent to which group work was observed during a STEM lesson. To improve clarity and thus reliability of items, examples of complex student behaviours were added to illustrate their meanings (e.g., engagement and interdisciplinarity items, Part D, Appendix A). The revised iSTEM protocol was then reviewed by education experts in mathematics, engineering, and digital technology, two expert curriculum planning officers at the Ministry of Education, Singapore, specialising in primary and secondary science/STEM education, and shared at a meeting with other STEM education curriculum planning officers and at an international conference presentation. The collective feedback led to improved clarity in the protocol descriptions and organisation.

iSTEM Protocol Overview and Structure

The current version of the iSTEM protocol (Appendix A) comprises descriptions of the STEM phases, STEM tasks, and the PIE dimensions along with its design principles, as well as four parts to be completed. Part A captures basic information of the observed integrated STEM lesson, including the sequence of STEM phases and tasks. In Part B, the observer (1) records the duration of an observed STEM phase, (2) indicates the enacted STEM tasks and the nature of instructional activities within the STEM phase (i.e., teacher instruction, class discussion/presentation, group discussion/hands-on, or individual seat work/hands-on) via checkboxes, and (3) writes descriptive observation notes of the lesson. Besides instructions to record the participants (i.e., teacher and students) and contents of their speech and action, abovementioned descriptions of PIE and its design principles help guide the observer on what to notice. To gather evidence for extents of PIE enacted, the observer should observe one group's interactions during group activities, if any. Points (1) to (3) are provided in individualised tables labelled for each STEM phase; tables can be repeated as necessary as the lesson proceeds. This protocol design affords the capture of STEM phases in any sequence, including repeats. Tables for recapitulation of previous lesson and reflection on lesson are also provided as these were commonly observed features of STEM lessons that do not belong to any of the STEM phases. Parts C and D of the iSTEM protocol are completed post-observation. Using observation notes in Part A as evidence, the observer assigns a rating (between 0 to 3) based on the extent to which evidence was present for each of 10 items for the four design principles (Part C) and five items for the three-dimensional pedagogical outcomes (Part D). Rubrics with four levels of evidence for each item are provided, similar to the Dimensions of Success (DoS) observation tool (Shah et al., 2018).

Validity and Reliability Considerations

The iSTEM protocol design prioritises content validity as the items were designed using a coherent framework informed by the PDE framework. The framework serves to provide an explanation for why students demonstrate high productive interdisciplinary engagement, or not, by accounting for the extents to which the four design principles are enacted and balanced in an observed STEM lesson. Review of the protocol by experts as abovementioned provided further support for its content validity.

Due to unforeseen delays associated with the COVID-19 situation, only initial efforts have been made towards establishing the protocol reliability. Two of the authors individually coded eight STEM lesson videos (four each at the primary and secondary levels, approximately ten hours of recordings in total). Due to the small sample size (n=8) and well-trained raters with low likelihood of guessing the ratings, we chose to use percent agreement as the indicator of inter-rater reliability instead of Cohen's kappa, which requires a recommended sample size of at least 30 (McHugh, 2012). The percent agreement for the protocol items ranged from 100% (three items), to 88% to 63% (nine items), to 50% to 38% (three items). We acknowledge that the latter three items–interdisciplinarity (50%), authority: teacher involvement (38%), and accountability: criteria nature (38%)–did not achieve satisfactory inter-rater reliability based on the existing sample. Nevertheless, we chose to retain the items as they are highly relevant to the PIE framework. Moreover, the two coders could reach consensus ratings on all the items through discussion, suggesting that the reliability is likely to improve as more video samples are coded. We have also indicated in the iSTEM protocol (Appendix A) that the abovementioned three items have low percent agreement among raters and recommend the protocol users to review these item descriptions carefully when deliberating their ratings.

Analysis with iSTEM Protocol

The item ratings for one of the coded lessons are presented to illustrate how the iSTEM protocol could characterise and communicate the profile of an integrated STEM lesson in terms of the extents to which students' PIE and design principles were enacted. As the ratings are not intended to be interpreted as an interval scale, no single score is assigned to any design principle or the lesson (Wainwright et al., 2003).

STEM Lesson Context

The video footage was recorded as part of a study that observed enacted integrated STEM lessons in Singapore K-12 classrooms. Video recordings focused on whole class instruction and one group during group activities, modelling what an observer would likely attend to during classroom observation. The reported one-hour STEM lesson was the second of a two-part STEM lesson (henceforth, Pill Coating lesson 2) (Author, 2019). Working in groups of fours/fives, secondary school students (eighth grade equivalent) worked on the previously described pill-coating problem. Students were given a set of materials to make the coating for a chocolate candy that simulated the pill and a cup of vinegar to simulate the stomach. In lesson 1, the teacher instructed to the class on how an ingested pill makes its way through the human digestive system. Students also had some time to explore making their own pill coating in their groups.

iSTEM Lesson Profile

Pill Coating lesson 2 progressed through the STEM phases, tasks, and activities sequence shown in Figure 1. The teacher, who is trained in science teaching, recapped the problem and called on a group with the longest lasting pill coating from lesson 1 to share their “recipe”. Students then spent most of the lesson researching and developing the pill coating in their groups as they first made pill coatings that satisfied one criterion at a time before making the optimal coating that incorporated all three criteria. The observed group engaged in episodes of members-only and teacher-involved discussions, as well as brief discussions with peers from other groups, during the hands-on activity. The teacher concluded the lesson by summarising and reflecting on how the STEM activity resembled real-life drug development by pharmaceutical companies.

Figure 1

Pill Coating Lesson 2 Progression

STEM Phase	**Recap**	**Research and Development**	**Reflection**
STEM Task	*Context, Problem, Development*	*Investigate, Concretise/Make, Test*	
Activity	Teacher instruction	Group members-only + teacher-involved discussion Group hands-on; Inter-group discussion (limited)	Teacher instruction

Figure 2

Pill Coating Lesson 2 iSTEM Profile–Design Principles

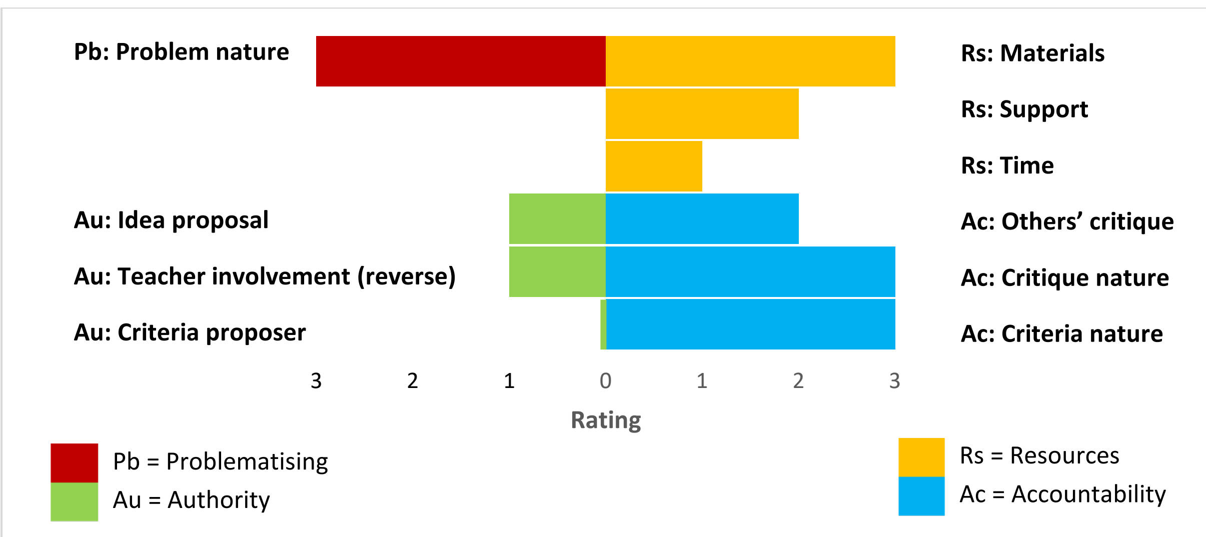
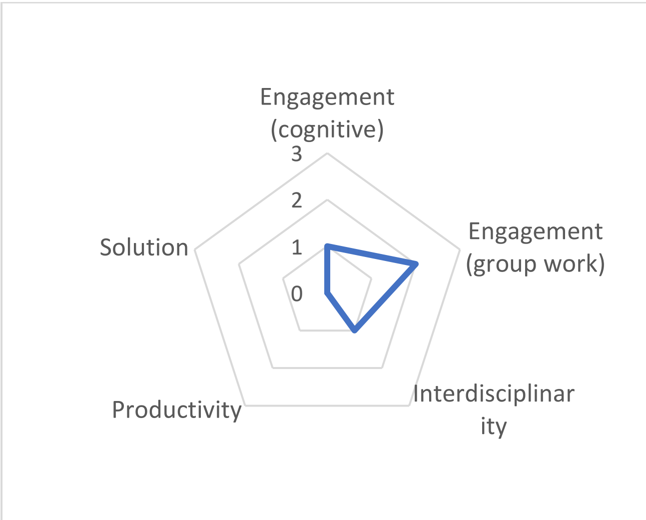


Figure 3

Pill Coating Lesson 2 iSTEM Profile–PIE



The iSTEM profile visually displays a lesson's design principles (Figure 2) and PIE extents (Figure 3). For brevity, we focus on how to interpret the iSTEM profile. Readers should refer to the iSTEM protocol items (Appendix A) to interpret specific ratings. The pill coating problem was considered a meaningful problem for students and STEM communities (rating=3 for the problematising item in Figure 2). Students were provided the necessary materials (rating=3) to produce the coating and adequate teacher support (rating=2), such as whole class instruction on how to proceed (produce three coatings that separately met a criterion before producing the final, optimised coating; how to divide the work among group members) and suggestion for the observed group on how to proceed with a particular investigation. Although the teacher modified the task by asking group members to divide the work by having a student pair produce a pill coating that met two criteria while the other pair produced a pill coating that met the remaining criterion as well as the optimised coating, the observed group only had time to produce pill coatings for one criterion (rating=1). Thus, problematising was not well-balanced by the resources to solve the problem, specifically with a lack in time as depicted in Figure 2. Notably, all three authority items were rated low. Students only proposed ideas with the teacher's support (rating=1) as the teacher mostly told students what to do (rating=1; this item has a reverse rating: the greater the teacher involvement, the lower the rating), including telling the class to include oil as an ingredient (based on the "recipe" shared by the group with longest lasting pill coating) and telling the observed group how much vinegar to use in their tests. Furthermore, all the criteria were given by the teacher and accepted by students without justification (rating=0). Conversely, accountability items were rated high as the group's ideas were mostly critiqued by the teacher (rating=2), with some critiques by their own members. Multiple critique instances referenced empirical data (checking amounts of flour/oil previously used to determine subsequent amount to use) and held the solution accountable to criteria (does coating need to last four minutes or could some ingredients be reduced to meet cost criteria) (rating=3 for critique nature). Furthermore, criteria considered sound disciplinary concepts/practices in two STEM disciplines (rating=3): scientific concept (that the pill coating should last a certain duration is based on the scientific concept of protecting the drug from the stomach acid) and mathematical reasoning (reducing amount of ingredients reduces cost of pill coating proportionally, based on ingredient costs).

The observed group demonstrated low PIE (Figure 3). Group members mostly engaged in information-seeking discourse (engagement (cognitive) rating=1) and completed tasks through division of labour, working in subgroups within the group (engagement (group work) rating=2). Students' decisions were often random and unjustified (e.g., students stated random amount of flour and oil to use, without justification), although the group did demonstrate disciplinary-based decision-making through the teacher's support (interdisciplinary rating=1). In terms of productivity, the group only produced the pill coating that met the criterion for durability, and it was not obvious how this was an improvement over their initial solution since lesson 1 (productivity rating=0). Thus, the group did not produce a final solution optimised to satisfy all criteria (solution rating=0).

Overall, the imbalance of authority and accountability, as well as a lack of time as a resource, might explain the group's low PIE. From the evidence for authority and accountability items, students in the observed group were not forthcoming in putting forward and deliberating their ideas. A possible reason might be that the teacher's insistence that groups produced separate solutions for the criteria before producing the optimal solution might not have made sense to the students (low student authority), especially if students did not understand the concept of optimisation. This is evident as students did not realise that they should reduce coating duration before the teacher prompted them to think so. Consequentially, students did not have sufficient time to produce all the necessary solutions (c.f. low rating for time as resource), resulting in low productivity. The teacher's insistence and thus assertion of authority at the expense of students' authority might also reflect the conventional classroom norms that the students and teacher were used to. Conventional science classrooms, which was familiar to the teacher, typically positions the teacher as the authority over the final form ideas in science which students are to acquire from the teacher (McNeill & Berland, 2017). Thus, students in the observed lesson might not be used to asserting their own authority and their teacher might not be comfortable with sharing authoriy with the students, for fear that the students might not succeed in their learning or task. The latter point is corroborated by the teacher's whole class instruction during Pill Coating lesson 1 where she insisted the students follow specific procedures to test their pill coatings, so that they would succeed in obtaining the results. As such, students might be unfamiliar with discourses involving critical discussions of their own ideas in systematic and discplinary-based decision-making, i.e. interdisciplinary engagement. Indeed, students and teachers might require extended practice before they adapt to the discourse norms of shared authority (Preston et al., 2020) that foreground epistemic aspects of a learning activity, such as why/how a phenomenon occurs in science inquiry (Preston et al., 2022) or how reasoned decisions are reached in integrated STEM activities. Another possible reason for the low PIE might be that the students did not find the problem personally meaningful, which resulted in the students not being engaged with seeking the best solution to the problem.

Conclusions

The proposed iSTEM protocol addresses a main shortcoming of previous K-12 integrated STEM classroom observation protocols (e.g., Dare et al., 2021; Peterman et al., 2017; Wheeler et al., 2019) by articulating a coherent set of design principles and corresponding pedagogical outcomes. Informed by the PDE framework (Engle, 2012; Engle & Conant, 2002), the iSTEM protocol serves as a viable tool to provide guidance on how to design integrated STEM experiences to meet desired pedagogical outcomes. The iSTEM protocol posits students' PIE in deliberating decisions towards a solution as a worthy integrated STEM education outcome, which was not articulated in the previous protocols. Additionally, the iSTEM protocol items corresponding to problematising, resources, authority, and accountability suggest ways through which these four design principles could be achieved and balanced to foster the 3-dimensional PIE outcomes. By articulating details of our protocol development, including our design considerations, rationale, and challenges, we hope to engage other researchers in the conversation of how to characterise and design "good" integrated STEM learning experiences.

Limitations

We highlight three main limitations with the current iSTEM protocol. Firstly, the inter-rater reliability should be further improved with a larger sample of video-recorded integrated STEM lessons. Since the iSTEM protocol is intended for use with live lessons, the reliability of live coding of lessons should be determined and compared with coding of video-recordings. A second limitation is that the protocol needs to be tested with a variety of K-12 integrated STEM lessons to ensure its usability across lesson designs and nature of integrated STEM problems. Thirdly, we recognise that it is possible for the four design principles to be met in ways not captured by the protocol items; likewise, for the indicators of productive interdisciplinary engagement as described in the items. Nevertheless, the items provide a relevant and coherent explanatory framework that highlights some important design principles to consider in integrated STEM learning experiences.

Potential Use of iSTEM Protocol

The fully developed iSTEM protocol will contribute towards STEM education in two ways. Firstly, the protocol serves as a research tool for STEM education researchers to analyse K-12 integrated STEM lessons. We have illustrated how the iSTEM profile for a lesson could be used to identify strengths and inadequacies in design principles, imbalance in pairs of design principles, and the corresponding 3-dimensional pedagogical outcomes. Using the iSTEM protocol with a variety of integrated STEM lesson designs, we can characterise and identify trends across integrated STEM learning experiences, as well as theorise explanations for productive interdisciplinary engagement using problematising, resources, authority, and accountability design principles as an initial model.

Secondly, we intend for the protocol to be used as a pedagogical guide for STEM classroom teachers to improve their design of STEM learning experiences. The iSTEM profile, along with evidence from the written observation notes, could be used to communicate strengths and areas of improvements, and initiate conversations with teachers on how to improve their instructional design. As teachers might have concerns about using a protocol with a rating scale that implies evaluation of their teaching, a suggestion would be to convert the ratings into nominal categories for communication with the teachers (Wainwright et al., 2003).

Finally, when interpreting and communicating the iSTEM protocol ratings, we should be mindful that the iSTEM profile presents a snapshot of a single, integrated STEM lesson enacted likely as a part of a series of lessons. For greater reliability, observations of more than one lesson within a STEM activity or unit of work should be made to identify potential profile variations due to the nature of the STEM tasks.

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Appendix A

Integrated STEM Classroom Observation Protocol (iSTEM protocol) version 5.0
Information for Protocol Users

Context of Protocol Use

The iSTEM protocol is designed for use in primary and secondary STEM classrooms for analysing: (a) the extents to which students demonstrate **P**roductive **I**nterdisciplinary **E**ngagement (**PIE**) while solving a STEM problem and (b) the extents to which design principles for fostering students' PIE–problematizing, resources, accountability, and authority–were present in the learning environment i.e., **enacted** during observed lesson.

A STEM activity or unit of work may include several STEM lessons. Complete one set of iSTEM protocol for each STEM lesson observed.

Suitable STEM Activities for Observation

Any STEM unit of work observed using the iSTEM protocol should have the aim of students **designing a solution to a real-life STEM problem**. Students generally follow engineering design, design thinking, science inquiry and/or computational thinking approaches, and draw upon conceptual knowledge, procedural skills/methods, and/or practices in at least one other STEM discipline to solve the problem.

A STEM unit of work should broadly comprise 3 **STEM phases**: Problem Definition, Research, and Development. Each STEM phase comprises various **STEM tasks**. A STEM lesson could also open with a **Recap** of the previous lesson and close with **Reflection** of the overall STEM lesson/activity.
Thus, a STEM lesson could include the following **Lesson Features:** Recap, Problem Definition, Research, Development, and Reflection. Any lesson feature could be repeated and may not appear in the above listed sequence.

How to Use the Protocol

The protocol comprises 4 parts.

Parts	To Do
README: commonly used terms, STEM Task definitions, and Design Principles descriptions	Read the definitions and descriptions before the lesson observation. Be familiar with what the STEM phases and tasks refer to and what observation notes to take.
Part A: Overview of Observed STEM Lesson	Fill in during Lesson Observation. Fill in Table 1 at the end of the observation. Ensure the sequence of lesson features and STEM tasks correspond to sequence of tables in Part B.
Part B: Observation Notes	Fill in during Lesson Observation. Copy and insert a new table for each Lesson Feature as needed e.g., when Lesson Feature is repeated, STEM Tasks in a Lesson Feature are non-concurrent.
Part C: Design Principles	Give ratings after lesson observation. Cite evidence from Part B: Observation notes.
Part D: Productive Interdisciplinary Engagement	Give ratings after lesson observation. Cite evidence from Part B: Observation notes.

README (read before Lesson Observation)

Descriptions of Commonly Used Terms

Term	Definition / Examples
STEM problem	The STEM problem could be presented as a problem to be solved, a challenge to overcome, or a product to be produced (either in a concrete, physical form or as a drawing or other mode of representation) by the end of the STEM activity or unit of work.
Success criteria for final solution	What the final solution to the STEM problem needs to fulfil or be able to do (i.e., its function) to be considered successful.
Constraints of final solution	Limitations on the final solution that restrict the possible solutions e.g., types and amount of materials to use, size of solution.
Sound disciplinary concepts:	Examples: mathematically or scientifically accurate concepts/facts.
Disciplinary practices/ways of thinking and doing (WOTD)	Practices valued by disciplinary communities. Examples of scientific practices: Asking questions, planning and carrying out investigation, analysing and interpreting data, modelling, constructing explanations, argumentation, obtaining, evaluating and communicating information Examples of technological practices: Design thinking, sketching, woodwork/metalwork, prototyping, weighing impacts of technology on society and the environment Examples of engineering practices: Defining problems, determining/defining success criteria and constraints, brainstorming for solutions, evaluating existing responses/solutions to problem, weighing tradeoffs and optimizing solution, making, testing (including the use of digital analysis tools/simulations to test design), iteratively redesign solution, communicating ideas to clients. Examples of mathematical practices: Making sense of the problem, modelling the problem using appropriate mathematical concepts and tools, looking for patterns and mathematical structures, reasoning abstractly and quantitatively, persevering in solving problems, using appropriate tools strategically to solve problems, attending to accuracy and precision, applying computational thinking to simulate scenarios and solve problems, constructing and critiquing mathematical arguments, representing and communicating mathematical ideas and solutions. References for disciplinary practices: American Association for the Advancement of Science (AAAS) (1993). *The nature of technology*. Project 2061: Benchmarks for Science Literacy. The nature of technology. http://www.project2061.org/publications/bsl/online/index.php?chapter=3 National Governors Association Center for Best Practices & Council of Chief State School Officers. (2010). *Common Core State Standards for Mathematics.* https://learning.ccsso.org/wp-content/uploads/2022/11/ADA-Compliant-Math-Standards.pdf. NGSS Lead States. (2013). *Next Generation Science Standards*: For States, By States. https://www.nextgenscience.org/.

STEM Task Definitions

* Lesson Feature	^STEM Task Definition
Recap	Recap of previous STEM lesson where **previously known/shared ideas are repeated** to class.
STEM Phase: **Problem Definition**	(i) **Context**: Introduce context that gives rise to STEM problem e.g. background of problem including who, where, when, etc. (ii) **Problem**: Identify or state the STEM problem/challenge within the given context that students are required to solve. May include statement or identification of success criteria or solution constraints to be fulfilled by the final STEM solution.
STEM Phase: **Research**	Gather information and/or empirical data to inform solution design. May include: (i) **Search** • Search for existing information in online sources, given texts, etc. • Search for and/or evaluate existing responses (i.e., current products) or possible solutions to problem. (ii) **Investigate** Gather empirical data to inform solution, such as: • Gather information from potential users to understand/specific problems pertinent to users (e.g,. through interviews, surveys). • Carry out investigations using control of variables (COV) approach or utilise given data to identify relationships among factors [Scientific inquiry].
STEM Phase: **Development**	Development of solution to STEM problem. May include: (i) **Generate** • Describe (e.g., list of requirements or specifications) and/or create a visual representation (e.g. drawing, diagram, flowchart) of possible solution(s) [Technology/Design]. • Scaling and optimisation to determine resources required, size of product etc. [Mathematics]. • Includes iterative re-generation of ideas. (ii) **Concretize/Make** • Create or revise a design, model, prototype or other product (physical or computer-based) that can be tested [Technology]. • Includes iterative re-concretize/re-make. (iii) **Test** • Put design, prototype, model, or other product to test(s) and analyse data from test(s) to evaluate whether the success criteria of the final STEM solution are met. Testing of design could utilise digital analysis tools such as simulations. Testing may also involve potential users. (iv) **Feedback** • Present design solution (including final STEM solution) to other peers (not involved in one's solution design) or whole class for feedback • Reflect on recommended changes or improvements to design solution. • May occur after any other task.
Reflection	Summary of lesson or STEM activity; reflection on what is learnt from lesson or STEM activity.

PIE Design Principles and Outcomes Descriptions

<table>
<tr><th>Design Principles</th><th>Detailed Description</th><th>Observation Notes to Take (where observed)</th></tr>
<tr><td>Problematizing</td><td>Extent to which the STEM problem is a meaningful problem for students and STEM communities. This is based on the context and nature of the STEM problem as presented to students.</td><td>The STEM problem, including its context.</td></tr>
<tr><td>Resources</td><td>Extent to which resources are provided to support students in solving the STEM problem.
Resources include:
1) Material resources (e.g., information sources/readings; physical materials; tools) to complete STEM task. These include:
• Materials: e.g., hyperlinks to information sources, readings, videos etc. on context or problem
• Tools: instruments for measurements or making product; apparatus for carrying out investigations; personal learning devices for making sketches.
2) Students are provided support from teacher (or other adults) or written scaffold in worksheet (e.g. instructions or template for steps/procedures) to complete STEM task.
Support can be in the form of:
• Teacher does part of STEM task for student or demonstrates procedures/steps
• Teacher gives verbal or written instruction on how to complete part of STEM task (e.g. certain procedures/steps) without showing how it is done
• Verbal or written options for how to proceed with or complete part of the STEM task but students are not told what to do or choose
• Structured worksheet e.g. to record engineering design processes (e.g. Ask, Plan, Create, Test, Improve).</td><td>What and how materials, tools, or form of support are given to students.

Note down if it is observed that students are given resources but do not use them.</td></tr>
<tr><td>Authority</td><td>Extent to which students are given epistemic authority to construct the final solution to the STEM problem. This depends on:
• Opportunities for students to propose own ideas for STEM task.
• How teacher follows-up on students' reported ideas.
• How success criteria/solution requirements for evaluating final solution to STEM problem are decided</td><td rowspan="2">What happens after a student proposes an idea related to the STEM task at hand or solution to STEM problem: who says what
• Include examples of critique <u>instances</u>: who says what

What success criteria/constraints and how they come about.

An <u>instance</u> = talk around a decision to be made for the STEM task at hand or contributes to solution of STEM problem. An instance begins when a new decision is being discussed and ends when a decision is reached (including agreement to postpone decision-making or agree to disagree)</td></tr>
<tr><td>Accountability</td><td>Extent to which students' ideas and actions are held accountable to STEM disciplinary concepts, ways of thinking and doing (WOTD) and norms, by self and others (peers, teacher). This depends on:
• Who critiques students' ideas put forward during STEM task.
• Nature of critique (verbal, written or checklist): based on STEM disciplinary concepts or WOTD, request for evidence/reasoning, or practical reasons.
• Nature of success criteria or constraints for the final solution to the STEM problem.</td></tr>
<tr><th>Outcomes</th><th>Description</th><th>Observation Notes to Take</th></tr>
<tr><td>Productive Interdisciplinarity Engagement</td><td>Extent to which students are cognitively engaged in group-based interdisciplinary decision-making to progress towards a final solution to the STEM problem.</td><td>How decisions related to the STEM task at hand or solution to the STEM problem are reached by the group, including how groups justify their decisions.</td></tr>
</table>

Part A: Overview of Observed STEM Lesson

School: ------------------------ Level / Stream or band: ------------ Class: ------------ No. of students: ---------- Teacher(s): ------------------------

STEM lesson topic -- Lesson no. (e.g. 1) ------------ Date: ---------- Time: ------------------------

Table 1. Fill in sequence of lesson feature and STEM tasks for observed lesson. Insert columns as needed.

Time	E.g. 0815 – 0845						
***Lesson Feature** – ^concurrent Task(s)	Problem definition – Context & Problem						

Observer's Notes on Overall Alignment

Alignment between	Response (Please check)	Elaboration (highlight what is problematic and/or how to improve)
(i) Lesson objectives and overall STEM problem Whether lesson objectives (achieved by the end of the observed lesson) directly contribute to solving the overall STEM problem.	☐ Yes ☐ No	
(ii) STEM Tasks and lesson objectives Whether STEM tasks implemented in the observed lesson are aligned and logically connected to the lesson objectives.	☐ Yes ☐ No	

Part B: Observation Notes **[Note: Insert table for respective Lesson Feature as needed]**

Lesson Feature	Recap	Start time:		End time:	

STEM Task (check all boxes that apply):

☐**Context**: Introduce context that gives rise to STEM problem e.g., background of problem including who, where, when etc.

☐**Problem:** Identify or state a problem/challenge within the given context that students are required to solve. May include statement or identification of success criteria or constraints.

☐**Research**: Gather information and/or empirical data to inform solution. May include search and/or investigate

☐**Development**: Development of solution to STEM problem. May include generate, concretize/make, test, and/or feedback.

Instructional Activity (check all boxes that apply) **Seat work involves documentation of ideas/responses e.g. with worksheet*

☐Class: teacher instruction
☐Class: discussion/critique
☐Class: group presentation
☐Inter-group: discussion/critique
☐Group: members-only discussion
☐Group: teacher-involved discussion
☐Group: hands-on
☐Group: seat work*
☐Individual: hands-on
☐Individual: seat work*

Lesson Observation Notes

- Persons involved: Teacher (tr). Students (ss) or (S1, S2, S3…) if distinguishable.
- Content of action and speech, including questioning and responses.

Include descriptions of the following. Highlight parts of notes that serve as evidence for each design principle (according to assigned colour).

- Context and nature of STEM problem **(Problematizing)**
- Materials provided, if any **(Resources)**
- Success criteria and how they came about, if any **(Accountability)**
- What happens after students propose an idea related to the STEM task or solution to STEM problem; who says what **(Authority)**
    - Include examples of critique instances **(Accountability)**. Critique may be verbal, written, or a checklist.

Problematizing

Resources

Authority

Accountability

Lesson Feature	**STEM Phase 1: Problem Definition**	**Start time:**		**End time:**	

STEM Task (check all boxes that apply):

☐ **Context**: Introduce context that gives rise to STEM problem e.g. background of problem including who, where, when etc.

☐ **Problem:** Identify or state a problem/challenge within the given context that students are required to solve. May include statement or identification of success criteria or constraints.

Instructional Activity (check all boxes that apply)

**Seat work involves documentation of ideas/responses e.g. with worksheet*

☐Class: teacher instruction
☐Class: discussion/critique
☐Class: group presentation
☐Inter-group: discussion/critique
☐Group: members-only discussion
☐Group: teacher-involved discussion
☐Group: hands-on
☐Group: seat work
☐Individual: hands-on
☐Individual: seat work

Lesson Observation Notes

• Persons involved: Teacher (tr). Students (ss) or (S1, S2, S3…) if distinguishable. • Content of action and speech, including questioning and responses.

Include descriptions of the following. Highlight parts of notes that serve as evidence for each design principle (according to assigned colour).

- Context and nature of STEM problem **(Problematizing)**
- Materials provided, if any **(Resources)**
- Success criteria and how they came about, if any **(Accountability)**
- What happens after students propose an idea related to the STEM task or solution to STEM problem; who says what **(Authority)**
  - Include examples of critique instances **(Accountability)**. Critique may be verbal, written, or a checklist.
- How students discuss and make decisions; what issues were encountered; what decisions are reached **(PIE)**

Problematizing **Resources** **Authority** **Accountability**	**PIE [Record Group Talk]**

Lesson Feature	**STEM Phase 2: Research**	**Start time:**		**End time:**	

Concurrent STEM Tasks (check all boxes that apply) **[Note: Insert new Research table if tasks are non-concurrent]**

☐ **Search**

- Search for existing information in online sources, given texts, etc.
- Search for and/or evaluate existing responses to problem.

☐ **Investigate**

Gather empirical data to inform solution, such as:

- Gather information from potential users to understand/specific problems pertinent to users (e.g. through interviews, surveys).
- Carry out investigations using control of variables (COV) approach or utilise given data to identify relationships among factors [Scientific inquiry].

Instructional Activity (check all boxes that apply)

**Seat work involves documentation of ideas/responses e.g. with worksheet*

☐Class: teacher instruction
☐Class: discussion/critique
☐Class: group presentation
☐Inter-group: discussion/critique
☐Group: members-only discussion
☐Group: teacher-involved discussion
☐Group: hands-on
☐Group: seat work
☐Individual: hands-on
☐Individual: seat work

Lesson Observation Notes

- Persons involved: Teacher (tr). Students (ss) or (S1, S2, S3…) if distinguishable.
- Content of action and speech, including questioning and responses.

Include descriptions of the following. Highlight parts of notes that serve as evidence for each design principle (according to assigned colour).

- Context and nature of STEM problem **(Problematizing)**
- Materials provided, if any **(Resources)**
- Success criteria and how they came about, if any **(Accountability)**
- What happens after students propose an idea related to the STEM task or solution to STEM problem; who says what **(Authority)**
  - Include examples of critique instances **(Accountability)**. Critique may be verbal, written, or a checklist.
- How students discuss and make decisions; what issues were encountered; what decisions are reached **(PIE)**

Problematizing **Resources** **Authority** **Accountability**	**PIE [Record Group Talk]**

Lesson Feature	**STEM Phase 3: Development**	**Start time:**		**End time:**	

Concurrent STEM Tasks (check all boxes that apply) **[Note: Insert new Development table if tasks are non-concurrent]**

☐ **Generate (includes iterative re-generation of ideas)**

- Describe (e.g., list of requirements or specifications) and/or create a visual representation (e.g. drawing, diagram, flowchart) of possible solutions [Technology/Design].
- Scaling and optimisation to determine resources required, size of product etc. [Mathematics].

☐ **Concretize/Make (includes iterative re-concretize/re-make)**

- Create or revise a design, model, prototype or other product (physical or computer-based) that can be tested [Technology].

☐ **Test (includes iterative re-test)**

- Put design, prototype, model, or other product to test(s) and analyse data from test(s) to evaluate whether the success criteria/constraints. are met. Testing of design could utilise digital analysis tools such as simulations. Testing may also involve potential users.

☐ **Feedback**

- Present design solution (including final solution) to other peers (not involved in one's solution design) or whole class for feedback
- Reflect on recommended changes or improvements to design solution.

Instructional Activity (check all boxes that apply) **Seat work involves documentation of ideas/responses e.g. with worksheet*

☐Class: teacher instruction	☐Inter-group: discussion/critique	☐Group: members-only discussion	☐Individual: hands-on
☐Class: discussion/critique		☐Group: teacher-involved discussion	☐Individual: seat work
☐Class: group presentation		☐Group: hands-on	
		☐Group: seat work	

Lesson Observation Notes

- Persons involved: Teacher (tr). Students (ss) or (S1, S2, S3…) if distinguishable. • Content of action and speech, including questioning and responses.

Include descriptions of the following. Highlight parts of notes that serve as evidence for each design principle (according to assigned colour).

- Context and nature of STEM problem **(Problematizing)**
- Materials provided, if any **(Resources)**
- Success criteria and how they came about, if any **(Accountability)**
- What happens after students propose an idea related to the STEM task or solution to STEM problem; who says what **(Authority)**
  - Include examples of critique instances **(Accountability)**. Critique may be verbal, written, or a checklist.
- How students discuss and make decisions; what issues were encountered; what decisions are reached **(PIE)**

Problematizing **Resources** **Authority** **Accountability**	**PIE [Record Group Talk]**

Lesson Feature	**Reflection**	**Start time:**		**End time:**	

Instructional Activity (check all boxes that apply)

**Seat work involves documentation of ideas/responses e.g. with worksheet*

☐Class: teacher instruction
☐Class: discussion/critique
☐Class: group presentation

☐Inter-group: discussion/critique

☐Group: members-only discussion
☐Group: teacher-involved discussion
☐Group: hands-on
☐Group: seat work

☐Individual: hands-on
☐Individual: seat work

Lesson Observation Notes

- Persons involved: Teacher (tr). Students (ss) or (S1, S2, S3…) if distinguishable. • Content of action and speech, including questioning and responses.

Include descriptions of the following. Highlight parts of notes that serve as evidence for each design principle (according to assigned colour).

- Context and nature of STEM problem **(Problematizing)**
- Materials provided, if any **(Resources)**
- Success criteria and how they came about, if any **(Accountability)**
- What happens after students propose an idea related to the STEM task or solution to STEM problem; who says what **(Authority)**
  - Include examples of critique instances **(Accountability)**. Critique may be verbal, written, or a checklist.

Problematizing **Resources** **Authority** **Accountability**	**PIE [Record Group Talk]**

Part C: Design Principles (Complete based on Part B: Observation Notes)

Cite evidence gathered from lesson features in observed STEM lesson to rate extent to which each design principle is met.

Problematizing

Overall STEM problem presented to students is a meaningful problem for students and STEM communities.

	Evidence absent **0**	**Minimal evidence** **1**	**Reasonable evidence** **2**	**Compelling evidence** **3**
(i) Nature of overall STEM problem (**check all that applies**): ☐ **Complex**: Requires concepts/skills from more than one STEM discipline to solve. ☐ **Authentic:** Relevant to students' lives or real-life situations, including historical events. ☐ **Open-ended**: Has more than one possible solution. ☐ **Extended**: Cannot be solved by simple search for solution (e.g. on the internet); some cycles of tasks within the STEM Development phase are involved (e.g. re-make, re-test) ☐ **Persistent**: Occurs in other contexts; not once-off.	STEM problem is not meaningful: no criteria met.	STEM problem is minimally meaningful: 1 to 2 criteria met.	STEM problem is fairly meaningful: 3 to 4 criteria met.	STEM problem is highly meaningful: all five criteria met.

Design Principle: Problematizing	**Evidence**	**Rating**
(i) Nature of STEM problem	State the STEM problem.	Choose an item.

Resources

Adequate resources are provided to support students in solving STEM problem during observed **STEM phase(s):** Problem definition, Research, Development.

	Evidence absent 0	Minimal evidence 1	Reasonable evidence 2	Compelling evidence 3
(i) Material Resources Extent to which students are provided needful materials and tools to complete STEM task. Examples of materials: hyperlinks to information sources, readings, materials to make product Examples of tools: instruments for measurements or making product; apparatus for carrying out investigations; personal learning devices for making sketches.	**Students source** for **all required** materials and tools in **observed** STEM phases. E.g. Students search for information and bring materials and tools to make their own product or complete the product outside the lesson time.	**Students source** for **most required** materials and tools in **observed** STEM phase(s). E.g. Students bring most materials to make their product.	**Students source** for **some required** materials and tools in **observed** STEM phase(s). E.g. Students given readings with information and tools to use but bring some of their own materials to make their product.	**Students *do not need to* source** for **any required** materials and tools in **observed** STEM phase(s). **All required materials and tools are provided.** E.g. Students given readings with information, materials and tools/apparatus to make their product.
(ii) Support Extent to which students are provided support from teacher (or other adults) or written scaffold in worksheet (e.g. instructions or template for steps/procedures) to complete STEM task.	**No support** provided by teacher or worksheet.	**Two or more** instances of verbal or written **options** for how to proceed with/complete STEM task but students are not told what to do/choose. May Include structured worksheet to record engineering design processes.	**Two or more** instances of **verbal or written instruction** on how to complete **part** of STEM task (e.g. procedures/steps) **without showing** how it is done. May Include structured worksheet to record engineering design processes.	**Two or more** instances of **teacher doing part** of STEM task for student or **demonstrating procedures/steps** to complete part of the STEM task. Repeated demonstration of same procedure/step counts as one instance. May Include structured worksheet to record engineering design processes e.g. Ask, Plan, Create, Test, Improve.
(iii) Time Extent to which students have sufficient time to work on the STEM problem within the lesson.	STEM tasks are **not spontaneously modified** and some STEM tasks could **not be completed**. E.g., Part/All of a STEM task, especially towards end of lesson, was abruptly ended/skipped over.	STEM task is **spontaneously modified due to insufficient time,** but some STEM tasks could **not be completed**. E.g., Teacher reduced the number of variables to investigate but some groups could not complete investigations.	STEM task is **spontaneously modified due to insufficient time** and STEM tasks were **completed**. E.g., Teacher calls on some groups to present their solution but not others.	Lesson was completed as planned with no evidence of STEM task modification due to insufficient time.

Design Principle: Resources	Evidence (Give evidence from observed lesson features from Observation Notes)	Rating
(i) Material resources		Choose an item.
(ii) Support		Choose an item.
(iii) Time		Choose an item.

Authority

Students are given epistemic authority to construct solution to STEM problem.

	Evidence absent 0	Minimal evidence 1	Reasonable evidence 2	Compelling evidence 3
(i) Idea proposal Who proposes ideas during Problem Definition, Research, and Development phases and whether ideas are acknowledged.	Students mostly **do not** propose their own ideas.	Students mostly propose ideas that are not acknowledged by peers for discussion.	Students mostly propose ideas with teacher support for discussion.	Students mostly propose ideas that are acknowledged by peers for discussion.
(ii) Teacher's involvement in students' ideas How teacher follows-up on students' reported ideas.	Students **follow a set of instructions** to complete various STEM tasks.	Teacher mostly **tells** students what modification to make or what to do/use instead. Teacher uses command words or gives instruction.	Teacher mostly **suggests** alternative/modification/ improvement for students to consider. Use of phrases such as "Why don't you…? Have you tried…? How about…?	Teacher mostly critiques or highlights good points **without suggesting modification or improvement**
(iii) Determination of success criteria/solution requirements How success criteria or solution requirements for evaluating final solution to STEM problem are decided.	Given by teacher and **accepted by students** with or without explaining choice of criteria OR no criteria given.	**Selected by students from a given list** (e.g., by majority vote) without discussing reasoning behind choice.	**Negotiated between students and teacher** (E.g. teacher provides some criteria/requirements which are discussed to reach class consensus).	**Additional criteria are proposed by students** at the group level for their solution with justifications.

Design Principle: Authority	**Evidence (Give evidence from observed lesson features from Observation Notes)**	**Rating**
(i) Idea proposal		Choose an item.
(ii) Teacher's involvement	Note: This item has a relatively lower percent agreement among raters. Please review the descriptions carefully when deliberating this item rating.	Choose an item.
(iii) Determination of success criteria		Choose an item.

Accountability

Students' ideas and actions are held accountable to STEM disciplinary concepts and practices or ways of thinking and doing (WOTD), by self and others (peers, teacher).

- **Sound disciplinary concepts**: e.g., mathematically/scientifically accurate concepts/facts.
- Critiques involving **disciplinary practices/WOTD** consider, for example: (i) validity and reliability of processes to gather and/or analyse data; (ii) coherence of reasoning and with evidence (if relevant); (iii) agreement of data/evidence/claims with others' data/evidence or established disciplinary ideas/facts, (iv) norms for 2D/3D drawings to communicate ideas.
- **Request for evidence or reasoning**: e.g., "Why do you say that?"; "What's your evidence?"; "How do you know that?"
- **Practical reasoning**: e.g., reasoning based on what is easy, convenient, or fast to do.

	Evidence absent 0	Minimal evidence 1	Reasonable evidence 2	Compelling evidence 3
(i) Critique by others Who critiques students' ideas put forward during STEM tasks.	No opportunities for critique. Group/Class discussion or presentation does not involve critique.	Most critiques are made by own group members.	Most critiques are made by teacher.	Most critiques are made by teacher and students beyond own group members.
(ii) Nature of critique How students' ideas are held accountable.	No opportunities for critique or only one critique instance.	**Two or more**-critique instances involve **practical reasoning not part of success criteria or constraints**.	**Two or more** critique instances involve **request for evidence or reasoning** without considering soundness of STEM disciplinary concepts or practices/WOTD (which includes meeting of success criteria or constraints).	**Two or more** critique instances involve **soundness of STEM** disciplinary concepts or practices/WOTD, including meeting of **success criteria or constraints.**
(iii) Nature of success criteria or constraints for the final solution	**No success criteria** are made explicit to students OR STEM tasks do not involve holding students accountable to the success criteria.	All success criteria/constraints are based on **practical reasoning**	Criteria/constraints include **sound** STEM concepts/practices involving **only 1 STEM discipline**.	Criteria/constraints include **sound** STEM concepts/practices involving **two or more STEM disciplines**.

Design Principle: Accountability	Evidence (Give evidence from observed lesson features from Observation Notes)	Rating
(i) Critique by others		Choose an item.
(ii) Nature of critique		Choose an item.
(iii) Nature of success criteria or constraints	Note: This item has a relatively lower percent agreement among raters. Please review the descriptions carefully when deliberating this item rating.	Choose an item.

Part D: Productive Interdisciplinary Engagement (Complete based on Part B: Observation Notes)

Note: Judgement of Productive Interdisciplinary Engagement should be done either for observed group or at Class level, for all three dimensions.

One instance = discussion of a decision (to be) made during **STEM Phases** (Problem definition, Research or Development) that affects quality of solution to STEM problem.

Dimension	**Evidence absent** **0**	**Minimal evidence** **1**	**Reasonable evidence** **2**	**Compelling evidence** **3**
Engagement (i) Cognitive engagement: Students are cognitively engaged during the STEM lesson.	Students demonstrate mostly **exposition**. Exposition means teacher or one student shares/elaborates on his/her idea(s) most of the time. May include quick confirmation or acknowledgement/agreement by others. E.g., Making egg-drop device [**Exposition**] S1: Let's put newspaper around the egg. We can use all of it. S2: All? [**confirmation**] S1: Yeah, just wrap all of it around the egg. But crumple it first. S2: Okay. [**acknowledgement/agreement**]	Students demonstrate mostly **information-seeking** discourse**.** Information-seeking means some students **ask questions to seek information or clarification** of idea while mainly one student responds. E.g., [**Information-seeking**] S1: Let's put newspaper around the egg. S2: How much do we use? S1: All of it. S3: Just wrap around the egg? S1: Crumple it first.	**Two or more** instances of **idea-building** discourse. Idea-building means students **build on** an idea (by elaborating, adding details, providing examples, etc.), **without identifying errors/issues or critiquing** the idea. Idea-building must involve students other than the idea proposer. E.g., [**Idea building**] S1: Let's put newspaper around the egg. S2: Okay, we can use all of it. S1: Crumple it first. Then wrap around the egg. S2: How do we secure it? S3: Use the tape. Wrap the tape all around so the newspaper won't fall off.	**Two or more** instances of **critical discussion.** Critical discussion means students **build on and critique** an idea with justification (e.g., justify why an idea would not work or has an issue) OR students **discuss/compare multiple ideas.** E.g., [**Critical discussion**] S1: Let's put newspaper around the egg. S2: Why? S1: The newspaper will cushion the egg when it hits the ground. S3: But <u>the egg will still fall very fast.</u> We will need a lot of newspaper. <u>I don't think there's enough newspaper</u> [**<u>critique</u>**]. S2: We can make a parachute. It will slow down the egg [discuss another idea]. Excludes isolated instances of quick identification of error/issue based on facts: Eg.. 1 S1: Let's use the glass. S2: This is plastic. E.g. 2 S3: We'll make it blue. S4: We don't have blue paint.
Engagement (ii) Students work in group or individually during the STEM lesson.	Lesson involves mostly **individual work OR** students are **not on task** during group or individual work.	Students mostly work **individually** during group work.	Students mostly work **within subgroups** of the group during group work.	Students mostly work **within the group** during group work.

Dimension	Evidence (Give evidence from observed lesson features from Observation Notes)	Rating
Engagement (i) Cognitive engagement		Choose an item.
Engagement (ii) Group vs individual work		Choose an item.

One instance = discussion of a decision (to be) made during **STEM Phases** (Problem definition, Research or Development) that affects quality of solution to STEM problem.

Dimension	Evidence absent 0	Minimal evidence 1	Reasonable evidence 2	Compelling evidence 3
Interdisciplinarity Students take a systematic and disciplinary-based approach to make and justify decisions that affect the quality of the solution to the STEM problem.	Students demonstrate mostly **random decision-making or unjustified decision-making.** Reasons for decision are not made explicit.	Students demonstrate mostly **poor decision-making** based on **satisficing** (i.e., agree with first idea that appears to meet success criteria/constraints) or **practical reasonings NOT tied to success criteria/constraints.** OR Students only demonstrate systematic disciplinary or non-disciplinary decision making with teacher involvement.	Students demonstrate **two or more instances** of **systematic but non-disciplinary-based decision-making**. Decisions are based on weighing benefits and tradeoffs, evidence (researched/given information or data from investigation/test), and **practical reasonings tied to success criteria/requirements**. Do NOT include disciplinary reasonings.	Students demonstrate **two or more instances** of **systematic and disciplinary-based decision-making**. Decisions are based on weighing benefits and tradeoffs, evidence (researched/given information or data from investigation/test), and **disciplinary reasonings** tied to success criteria/requirements.

Dimension	Evidence (Give evidence from observed lesson features from Observation Notes)	Rating
Interdisciplinarity Rate based on highest level observed.	Note: This item has a relatively lower percent agreement among raters. Please review the descriptions carefully when deliberating this item rating.	Choose an item.

Dimension	Evidence absent 0	Minimal evidence 1	Reasonable evidence 2	Compelling evidence 3
Productivity (i) Students make progress towards the solution to the STEM problem, from start to end of the STEM lesson.	Students do not reach a required decision/solution for STEM task(s) by end of lesson. No issues with proposed decision/solution are identified (by students or teacher).	Issue(s) with initial decision/solution are identified (by students or teacher), which makes it inadequate, but students do not reach improved decision/solution by end of lesson.	Students successfully defend decision/solution against critiques without modifying it OR solution satisfies all tests and thus does not require modification.	Students reach a new or improved decision/solution that addresses an issue or meets more *success criteria/constraints* by end of lesson (compared to their initial idea).
Productivity (ii) Quality of final solution to STEM problem.	Most students' final solution does not meet any success criteria OR There is no approach to determine if students' final solution met any success criteria. OR No final solution is produced.	Most students' final solution meets **fewer than half** of the success criteria OR satisfies fewer than half of the constraints.	Most students' final solution meets **more than half** of the success criteria AND satisfies more than half of the constraints.	Most students' final solution meets **all** of the success criteria. AND satisfies all constraints.

Dimension	Evidence (Give evidence from observed lesson features from Observation Notes)	Rating
Productivity **(i) Progress towards solution**		Choose an item.
Productivity **(ii) Quality of final solution**	Only applicable for lesson involving final STEM solution. Summarize quality of final solution by various students/groups and most frequently met success criteria/requirements	Choose an item.