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How do interdisciplinary teams co-construct instructional materials emphasising both science and engineering practices?

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ABSTRACT

To build a sustainable future, science and engineering education programmes should emphasise scientific investigation, collaboration across traditional science topics and disciplines, and engineering design, including design and evaluation of solutions. While some research studies articulate the shifts that are needed to realise classroom learning emphasizing investigation and design, fewer research studies help us to understand how we co-design these instructional programmes, including how experts from different essential disciplines collaborate towards an interdisciplinary instructional programme. We adopted a qualitative case study design to address the research question, *What is the process of team co-construction of instructional materials that emphasize learning through both science investigation and engineering design?* The paper outlines the first year of our team co-construction activities involving the design, implementation, and evaluation of instructional materials for secondary science. Qualitative data included semi-structured interviews with nine team members and documentation in form of researcher field notes and learning artefacts. Two cycles of coding resulted in five major themes that served as the basis for the five-phase model of team co-construction of instructional materials. This study provides information on the kinds of partnerships and collaboration needed to realise instructional programmes for students' study of the interdisciplinary STEM-based challenges of tomorrow.

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Introduction

The modern world faces complex and interdisciplinary environmental, social, and economic challenges with foundations in Science, Technology, Engineering, and Mathematics (STEM) disciplines. Enhancement of PreK-12 students' STEM knowledge and skills, including science investigation and solution generation, is critical in preparing future STEM workforce to cope with complex challenges in today's world (Committee on STEM Education of the National Science & Technology Council, 2018; National

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Research Council (NRC), 2019; Rahman et al., 2021; National Academy of Engineering (NAE), 2009). STEM education policy reports recognise the importance of fostering science investigation and solution generation, often represented by the steps of engineering design, as a foundation for STEM learning (Office of Science and Technology Policy, 2020; Committee on STEM Education of the National Science & Technology Council, 2018; NRC, 2019; NGSS Lead States, 2013). As outlined by the report, 'The Future of Education and Skills: Education 2030' (Organization for Economic Cooperation and Development, 2018), to build a sustainable future, educational programmes should be geared toward learning that emphasises scientific investigation, collaboration across and between areas of expertise, and engineering design, including design and evaluation of solutions.

Despite policy documents that emphasise the design of solutions as a foundation to STEM learning, many pre-college STEM instructional programmes do not promote the design and evaluation of solutions as part of science curricula (NRC, 2019). We speculate that this lack of programmes that emphasise solution generation to foster and deepen students' understandings of STEM content is due, in part, to the lack of high-quality instructional materials that foster this kind of pre-college STEM learning. A recent study on STEM secondary education in Indonesia called for a need to shift science teacher training and professional development toward systematic and ongoing lesson analysis and integration of effective STEM practices (Permanasari et al., 2021). Understanding the design of interdisciplinary, solution-generation STEM instructional materials and learning environments is crucial in supporting the new vision for K-12 science education (NRC, 2012). In this study, we use the term 'instructional materials' as an umbrella term to denote a suite of resources consisting of curricular, assessment, and professional development (PD) materials.

Policy documents that draw from multiple empirical studies also document the value of local-problem-focused science activities. For example, when describing phenomenon-focused activities, the National Academies of Sciences' Framework (NRC, 2012) states that students' 'appreciation of the interface of science, engineering, and society should give them deeper insight into local, national, and global issues.' (NRC, 2012, p. 203). Similarly, the National Academies of Sciences' 2019 report states, 'Science investigation and engineering design can allow students to participate in science as a social enterprise and help them to connect science and engineering concepts and principles to their own experience and ideas' (NRC, 2019, p. 11). This report also cites empirical studies demonstrating that learning through science investigation and engineering design is more effective than learning through more traditional teaching methods (NRC, 2019). Research showed that implementation of engineering design process across STEM disciplines enhanced learners' understanding and knowledge of STEM content, problem-solving skills, as well as technological literacy (Galoyan, 2022; Guzey et al., 2017; McGowan & Bell, 2020).

While studies characterise and evaluate STEM instructional programmes that emphasise learning through science and engineering practices (e.g. asking questions (for science) and defining problems (for engineering); developing and using models; planning or carrying out investigations; analyzing and interpreting data) (NRC, 2012), further research is needed to articulate the kinds of collaboration and steps involved in the interdisciplinary co-design of STEM instructional programmes that emphasise learning through both the science and engineering practices (Christian et al., 2021; Coburn et al., 2013; NRC, 2012). The Committee on Facilitating Interdisciplinary Research (2004), a section of the Committee on Science, Engineering, and Public Policy, described interdisciplinary research as:

A mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialised knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice. (p. 2)

Previous studies articulated the need for interdisciplinary collaboration for enhancing teaching and research in STEM disciplines (Bouwma-Gearhart et al., 2014; Kilty et al., 2021). For example, a study by Bouwma-Gearhart and colleagues (2014) identified key characteristics that help to establish and maintain successful interdisciplinary collaborations among STEM and Education faculty. Some of these characteristics included recognising the value of other's expertise, recognising differences in team members' professional paths and expertise regarding pedagogical issues, connecting with more knowledgeable experts, and framing Education research and theory with respect to STEM research and pedagogical practices.

More studies are needed to understand how to achieve optimal STEM integration that is characterised by evidence-based decision-making (NAE, 2009; Purzer & Quintana-Cifuentes, 2019). We need research studies that document the roles of individual and group members of the interdisciplinary team, including the kinds of work and collaboration among curriculum developers, teachers, students, scientists, software developers, and community members and stakeholders. Such studies are needed to provide practitioners and researchers with guidance on how to effectively and collaboratively design STEM instructional materials that realise the vision.

Funded by the United States' National Science Foundation, this study adopted a qualitative case study design to address the research question, *What is the process of team co-construction of instructional materials that emphasize learning through both science investigation and engineering design?* The paper outlines the first year of our team co-construction activities involving the design, implementation, and evaluation of eight-weeks of instructional materials for middle school teachers and students.

Conceptual framework

The conceptual framework that served as a lens for this research on interdisciplinary team co-construction processes is comprised of two main components, namely (1) situated learning approach (Lave & Wenger, 1991); and (2) our learning approach called Eco-Solutioning. The following sections discuss each approach as it related to our team co-construction process of science instructional materials.

Situated learning

The co-construction of interdisciplinary instructional materials was guided by the theories and principles of the learning sciences including the situated learning approach (Holland & Lave, 2009; Lave & Wenger, 1991; Pellegrino, 2020; Rogoff et al., 2007).

Situated learning focuses on the contextualised nature of human understanding and communication and defines learning in terms of social co-participation and the relationships between learning and the social context in which learning occurs (Lave & Wenger, 1991). Socially constructed situated learning reflects the shift from characterising science knowledge in terms of individual cognitive processes to viewing science knowledge as socially co-constructed within a social and cultural context (Pellegrino, 2020; Songer & Kali, 2022). This study has adopted the situated learning approach at two levels, namely (1) the instructional materials; and (2) research team co-construction process. At the level of instructional materials, the situated learning approach helped to design activities that aimed to situate learners in authentic science and engineering experiences and knowledge co-construction. At the level of research team activities, the situated learning approach served as the foundational framework to study the process of multidisciplinary team collaboration and co-construction in the context of designing science instructional materials.

In designing science instructional materials, the situated approach has led to the creation of contextualised and rich learning experiences where participants' experiences are situated in meaningful social endeavours. Next Generation Science Standards (NGSS) emphasise the importance of situating science curricula in meaningful and relevant problem solving and argumentation to help students reach deeper understanding of the science content (NRC, 2019). According to Penuel and Reiser (2018), NGSS-aligned instructional programmes need to emphasise several features, among which are three-dimensional learning (3D)[1] and the central role for phenomena and design challenges. Similarly, policy reports such as those from the United States National Academies of Sciences (e.g. NRC, 2019) emphasise the importance of situating science activities in meaningful and relevant problem-solving contexts (NRC, 2019). Penuel and Reiser (2018) noted that 'Engagement in science and engineering practices requires that students' participation is directly motivated by their goals of making sense of phenomena or solving problems they have identified' (Penuel & Reiser, 2018, p. 1). In utilising the situated learning approach as a foundation for the design of science instructional materials, our activities were designed to situate both student learning and researcher co-construction work in local and social contexts. To successfully implement this new vision, the team needed to organise and study new forms of partnership and collaboration. As discussed in Penuel and Reiser (2018), to facilitate participation in the educational processes that support the vision, 'new kinds of individual and social capacities' needed to be developed. (p.34) Scientists and curriculum developers needed to work closely to be able to design instructional materials around engaging and relevant science phenomena and issues.

Eco-solutioning

Other researchers have articulated learning approaches that emphasise learning science content through either science practices, such as Bybee's (2006) 5-Es model, or engineering practices, such as learning through Engineering Design (e.g. Crotty et al., 2017; Guzey et al., 2017; NGSS Leads States, 2013). The need to explicitly articulate the interconnected nature of both science and engineering practices has been fulfilled through a learning approach called eco-solutioning (Songer & Ibarrola Recalde, 2021). The Eco-solutioning learning draws from Bybee's (2006) 5Es instructional model of Engage, Explore, Explain, Elaborate, and Evaluate. In Eco-solutioning, the 4th and 5th learning phases of Bybee's 5Es model (Elaborate and Evaluate) are revised to emphasise Engineering and Education (Table 1). This shift provides a sequence of activities that extend students' learning of science through the science practices to the engineering practices of defining problems and designing solutions (Table 1). In other words, students first learn about local science content (ecology and organisms) through the science practices of question generation, data collection, data analysis, and using data as evidence to construct arguments. Later in the unit, students deepen their learning of science content through the engineering practices of designing, testing, and sharing a solution to a local environmental problem.

Methods

Research design

This study is part of a larger research project that examines the design, usability, implementation, and evaluation of a suite of instructional materials that include curricular activities, assessment, and professional development materials for middle school students and teachers. We adopted a qualitative case study design (Merriam, 2009; Yin, 2014) to address our research question that explores the process of interdisciplinary team co-construction of instructional materials that emphasise learning through both science investigation and engineering design. Yin (2014) defines a case study as 'an

Table 1. Comparison of Bybee (2006) 5Es and Eco-Solutioning 5Es Instructional Models.

Original 5E (Bybee, 2006) Instructional Model		Eco-Solutioning 5E Instructional Model	
Phase	Description	Phase	Description
Engage	An activity that helps students become engaged in a new concept and promotes curiosity in the content	***Engage***	Students **ask questions** associated with an introductory activity that engages their curiosity and provides a purpose for why they are studying local environmental issues
Explore	Activities facilitate the learner's connection between current understanding and scientific ways of thinking. Through these activities learners 'use prior knowledge to generate new ideas, explore questions and possibilities, and design and conduct a preliminary investigation.'	***Explore***	Students **collect data** on animal/plant species within their local neighbourhood to **use as evidence** to address a problem in their neighbourhood
Explain	Students have opportunities to develop their conceptual understanding, process skills, or behaviours around target content. Concepts, processes, or skills are directly introduced to help guide students towards deeper understandings	***Explain***	Students **use evidence** from the Explore phase students **construct an argument** to address a scientific question
Elaborate	Students are challenged to extend their understanding to develop broader understandings of content, processes, and skills. Additional activities allow students to apply their understanding to new contexts	***Engineer***	Students **design** an eco-solution plan that meets specific design criteria and constraints. Students **test** their plans to determine which solution is optimal for addressing the problem
Evaluate	Students are encouraged to assess their understanding and abilities around target content. Teachers are able to evaluate students' progress	***Educate***	Students synthesise guidelines from their eco-solution plan to inform and **educate** key stakeholders about the ways the plan might be implemented in their own and other local regions

empirical inquiry that investigates a contemporary phenomenon (the 'case') in depth and within its real-world context' (Yin, 2014, p. 16). In the present study, the case is the particular activity (Merriam, 2009) characterising the co-construction (e.g. collaborative design process) of the instructional materials. The case was bounded contextually and temporally to the processes and decision points of the research project team members. Two team members participated in both data generation and data analysis and therefore assumed the role of participant-observers who 'see things firsthand and use [their] knowledge and expertise in interpreting what is observed … ' (Merriam & Tisdell, 2016, p. 139).

The case study protocol included two types of qualitative data sources: (a) semi-structured interviews with nine team members, which was the primary data source; and (b) documentation of the co-construction activities by the team members in form of field notes and learning artefacts (e.g. the curriculum, lesson plans, learner-created artefacts, etc.). Documentation served as a secondary data source that helped to compliment and corroborate the findings from the interviews. The strengths of interviews as a data source for a qualitative case study are (a) they directly focus on the case study topic; and (b) they are insightful, meaning they can provide explanations and reveal personal views on a given topic (Yin, 2014). The strengths of documentation as a source of evidence for a case study are (a) they are both stable and specific, meaning they can be reviewed repeatedly and can contain the exact names, and details of an event; (b) they can cover a broad timespan, multiple events, and settings (Yin, 2014).

Interview protocol

The team developed a semi-structured interview protocol to facilitate the interview process (Merriam & Tisdell, 2016). The interview protocol consisted of nine broad questions that explored various aspects of the research team co-construction activities, the specific team member involvement, and their role in the project. Two sample questions from the interview protocol are presented in Table 2 and the entire protocol is available upon request.

Participants and data collection

We conducted semi-structured interviews of 40 min to 1-hour duration with each member of the research team ($N = 9$). There were 8 female and 1 male participants representing a variety of main expertise areas including 4 STEM educators, 2 learning technology designers, 2 scientists, and 1 middle school teacher. It is worth noting that, in addition to our middle school science teacher, six out of the other eight team members had experience in classroom teaching. The participants' experience in the area varied from 5 to 23 years (Table 3). Interviews were conducted and recorded by using the Zoom video-conferencing tool.

Documentation

A second data source was field notes taken by the research team members based on multiple sources such as the agendas and minutes of team meetings, emails, calendar notes,

Table 2. Sample Questions and Exemplar Quotes from Semi-structured Interviews ($N = 9$).

Sample Question	Exemplar Quote
Looking at the timeline, in what pieces of work did you participate? a. What did you do? b. Who worked with you on these pieces?	*… I work directly with our engineering and tech. team and data science team to basically help develop … I'm working with our technology team … making sure we have all those features, making sure the students have a navigator experience and skyline, building competency frameworks and then working with the curriculum team on curriculum pieces, lesson planning, and then also make sure the lesson plans can go into the navigator system successfully and sort of have that cohesive experience for the learner and instructors.* [Participant E] *I was involved in most of the activities in year one of the project. I was involved in the curriculum development, assessment development, and research. For the curriculum development, we started with the PI mapping out the curriculum plan and establishing the anchor goals … then we established the specific learning goals for each lesson. And after that we started working within our curriculum team to develop the curriculum story further and to map out the activities.* [Participant B]
Of the pieces of work in which you participated, which of those involved co-construction across different individuals and different areas of expertise?	*I would say absolutely every piece because, from the competency framework, I worked with the PI and the post-doctoral researcher and then the other graduate students on the project to better understand the curriculum story, we went back and forth quite a bit about how we are merging the practice and the DCIs* [Disciplinary Core Ideas] *and what the actual objectives and goals are … So there's a lot of back and forth between content experts, curriculum experts, and basically everyone involved in the project to make sure the story is cohesive. There's a lot of back and forth between myself and our tech team to make sure that our technology is developed in a way that's most useful for the learner and the teacher.* [Participant E]
Now we'd like to ask some questions about the process of co-creation of the instructional and assessment materials that we are developing associated with the pieces of work that you identified above. For each of these pieces of work that involved co-construction: a. How would you describe the process of co-construction? In other words what do you and others do first, second etc.? b. What were some of the ways in which individuals worked together?	*'It is the primarily resource development, so I've been working with both our content and database developer, as well as finding and supervising an external web developer, as well as some content developers, some people who are developing new content for us that is necessary … I've been part of conversations around the curriculum and ideas about how to implement that, so that's, I think clearly co-construction across disciplines.* [Participant I] *So, as the principal investigator, I feel like it's my job to outline the different categories of work, such as curriculum development, assessment, development, research, et cetera, and then to guide and support other people in taking ownership and leadership in some of those pieces.* [Participant A] *We were collaborating with the technology team and biology resources team throughout the whole process. But it was for some pieces we were just within our small teams and then we would hand it over to the other teams.* [Participant B]
What challenges did you experience in the co-construction work? How, if at all, were those challenges overcome? If they were not overcome, what do you suggest we do next?	*… the process of collaboration is challenging, and it can be, like any other project, if we want to make things from scratch and if we want to make something new, it's always challenging … the only thing I can say is embracing this uncertainty, challenging nature of the activity, helped me a lot … the PI of the project helped a lot in terms of suggesting different materials and resources from the previous projects* … [Participant F]

(*Continued*)

Table 2. Continued.

Sample Question	Exemplar Quote
What are any additional takeaways about the process of co-construction of instructional materials from year one of the project?	*I think the biggest takeaway is that as we're harnessing and sort of bringing different expertise together, it makes it very powerful. If we can continue to foster that, as well as continue to iterate quickly, I think that's a really nice piece.* [Participant E] *I can say I've learned a lot from this project and from this process of co-construction. I really enjoyed collaborating with multiple people with multiple backgrounds and areas of expertise. I think it was really rewarding.*[Participant B]

Table 3. Participant Characteristics.

Participant	Area of Expertise	Role in the Project	Years of Experience	Gender
A	STEM Educator	Principal Investigator (PI)	23	F
B	STEM Educator	Postdoctoral Scholar	12	F
C	STEM Educator	Graduate Research Assistant	15	M
D	Learning Technology Designer	Graduate Research Assistant	9	F
E	Learning Technology Designer	Co-PI	6	F
F	STEM Educator	Graduate Research Assistant	5	F
G	Middle School Science Educator	Classroom Teacher	6	F
H	Scientist	Graduate Research Assistant	15	F
I	Scientist	Co-PI	20	F

progress reports, and learning artefacts. These field notes were collected into a single researcher-generated digital spreadsheet. As discussed in Merriam and Tisdell (2016), in qualitative research, researcher-generated documents help to gain insight into 'the situation, person, or event being investigated.' (p. 174). In our case, the purpose of the field notes was to document the chronology and type of team co-construction activities and related learning artefacts. Specifically, the spreadsheet chronologically organised each major task representing personnel, type of activities, tasks within each activity, progress and status of each task, and duration. The completed spreadsheet consisted of 47 rows, 5 types of activities, 38 tasks, and 12 months of project teamwork. Figure 1 illustrates a section of the field notes representing approximately 20% of the total spreadsheet.

Data analysis

Two sources of evidence, the interviews and the field notes, were analyzed using the ATLAS.ti qualitative data analysis software. The analysis steps aligned with general guidelines for qualitative data analysis (e.g. Merriam & Tisdell, 2016; Smith & Osborn, 2008; Strauss & Corbin, 1997). The following sections present the steps of our data analysis.

Step 1: data preparation and creation of a codebook with initial codes

Step 1 of the data analysis started with transcribing and importing interview transcriptions into the qualitative analysis software. After entry, multiple reviews of each transcript were conducted and accompanied by extensive note taking in the form of analytic memos. Next, we conducted the initial data analysis involving Level 1 coding of the qualitative data from the interview transcripts and the spreadsheet with the field

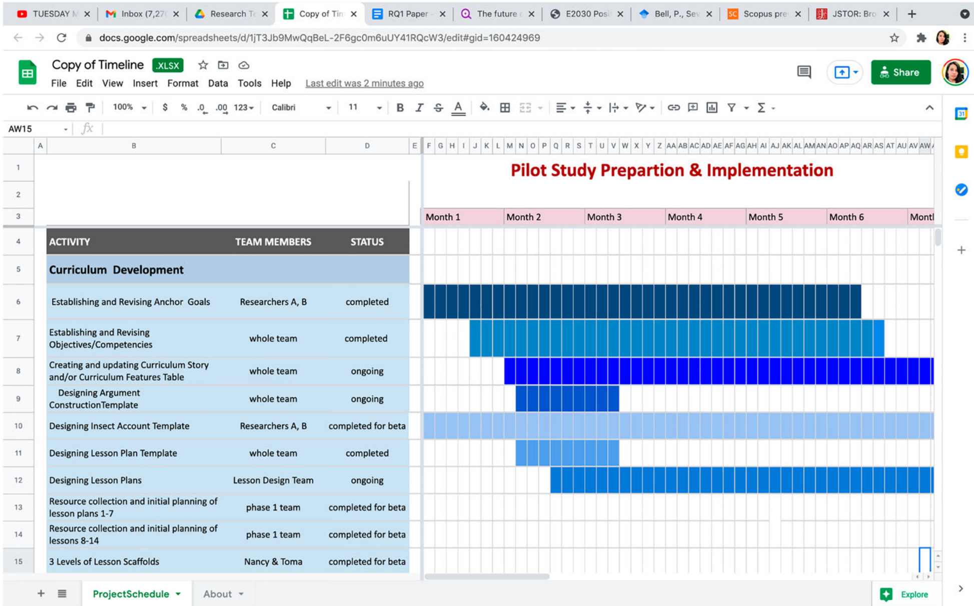

Figure 1. A screenshot of a section from the field notes. The section on the left lists the specific activities, the team members involved, and the progress report for each activity. The right section indicates the timeline for each activity. Note that this figure represents approximately 20% of the information contained in the spreadsheet.

notes. We analyzed each transcript separately by applying an open coding technique where we assigned a code to a specific segment of the transcript (Patton, 2002). The same strategy was applied to the spreadsheet with the field notes. Level 1 coding allowed for the generation of the initial codebook that contained multiple codes related to the team co-construction activities, including major activities, specific tasks within each activity, the timeline for each task, and the team members involved in each task. Table 4 below illustrates a small section of the initial codebook.

Step 2: identifying patterns and clustering codes into themes

In Step 2, we conducted Level 2 coding that involved seeking associations and patterns and clustering the initial codes from Step 1 into broader themes and sub-themes.

Table 4. Section from the Codebook.

Major Activity	Task	Experts Involved	Timeline
Curriculum Development	Establishing NGSS Anchor Goals	A B	Months 1–2
	Establishing Learning Objectives	A B C D	Months 1–2
	Establishing 3 Levels of Scaffolding	A B	Months 3–6
	Developing Curriculum Story	A B C D	Months 2–8
	Designing Scientific Argument Construction Template	A B E	Months 1–2
	Designing Lesson Plans	A B C D F G H	Months 3–6
	Establishing synchronous and asynchronous elements	A B E	Months 7–8
Assessment Development	Developing Assessment Template	A B C D F H	Months 1–2
	Incorporating 3 levels of scaffolding		Months 7–8
	Developing summative assessment items		Months 3–6
	Developing formative assessment Items		Months 3–6
	Developing a rubric for the solution project		Months 3–7

Level 2 coding resulted in identification of five major themes and related sub-themes that ultimately formed the proposed five-phase model of team co-construction activities discussed in the following Findings section.

Findings

The analysis of the qualitative data provided by two data sources – the interviews and the field notes – resulted in five major themes representing five distinct phases of the co-construction process, namely *Foundation, Multidisciplinary Construction, Multi-Resource Integration, Multimodal Implementation*, and *Analysis & Recommendations*. Figure 2 illustrates the five phases of the co-construction process, as well as the related sub-themes representing the specific end products, duration, and experts involved in each phase.

Phase One: foundation

Phase One, Foundation, reflects the conceptualisation of the co-construction of the instructional materials that emphasise learning through both science investigations and engineering design. This phase involves identifying and sequencing activities that comprise the co-construction process. These foundational activities include determining the curriculum anchor goals, breaking into teams and delegating tasks, establishing the learning goals for each lesson, and creating templates for particular activity types. The expertise needed for this phase is one or more STEM educators who have a big picture understanding of the work, collaboration, and tasks.

In our case, first, two project leaders selected four NGSS-aligned performance expectations to serve as anchor goals for the unit. Next, the project leaders assigned other team

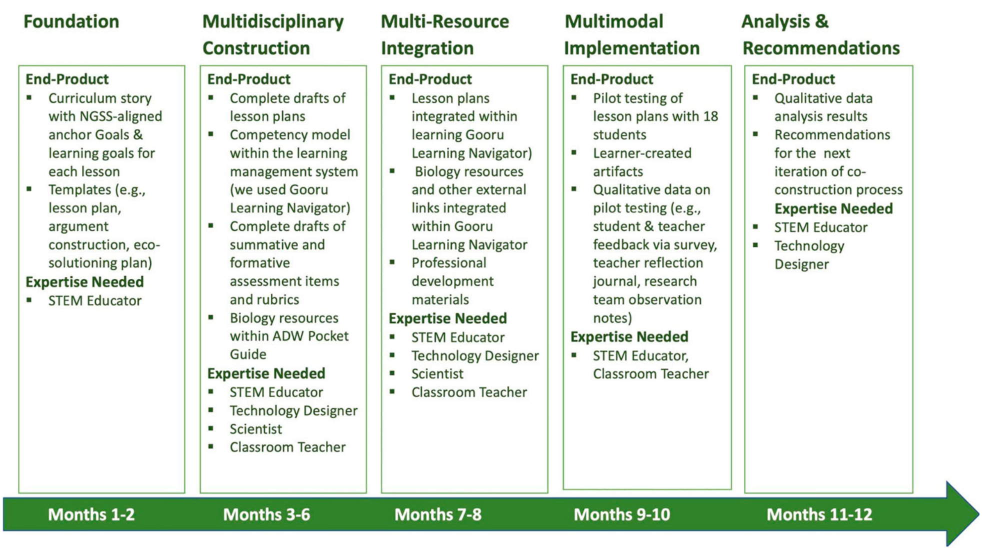

Figure 2. A Five-Phase Model of Team Co-construction of Instructional Materials That Emphasise Learning Through Both Science Investigations and Engineering Design.

members to one or more teams based on both their expected roles and areas of expertise. The teams were: Lesson Design (A, B, C, D, G) Assessment Design (A, B, E, H), Learning System (E, G), Biology Resources (G, I), and Research (A, B) (see Table 3 for participant characteristics). Once the anchor goals were determined, members of the Lesson Design team created a lesson sequence document called the Curriculum Story that articulated the NGSS anchor goals, related 3D components, and the learning goals in sequence and for each lesson (Table 5). The Curriculum Story was a result of multiple iterations and served as a master document that guided all the subsequent design of the coordinated instructional materials. Once the Curriculum Story was created, the Lesson Design team designed templates to standardise the format and delivery of the lessons and student work products. Example templates include the lesson plan template, scientific argument construction template, and eco-solution plan template. The end-products from Phase One included the Curriculum Story document and the multiple templates.

Phase Two: multidisciplinary construction

Phase Two, Multidisciplinary Construction, involves the active creation of the student and teacher versions of each lesson, coordinated assessments, as well as the development of biology and other resources as outlined in the Curriculum Story generated in Phase One. Phase Two work is distributed across multidisciplinary teams based on their

Table 5. A Section from the Curriculum Story Illustrating the NGSS Anchor goals, Related Dimensions of Science Learning (e.g. SEP, DCI, CCC), and the Learning Goals for Each Lesson.

Investigation Which insects live in my neighborhood?			
Lesson	Competency/Learning Goal	NGSS Anchor Goal	3D Learning (SEP, DCI, CCC)
1. What living things were observed in my city or town today?	Ask questions (SEP 1) about what living things were observed in my city or town today?	MS-LS2-1 Analyze and interpret data to provide evidence for the effects of resource availability on organisms and populations of organisms in an ecosystem	SEP 1 – Ask questions DCI – LS2.A: Interdependent Relationships in Ecosystems CCC – Cause and Effect
2. Is my animal an insect?	Analyze and interpret data (SEP 4), then use data as evidence to Engage in argument (SEP 7) to address the scientific question, Is my animal an insect?		SEP 4, SEP 7 – Analyzing/ interpreting/Argument DCI – LS2.A: Interdependent Relationships in Ecosystems CCC – Cause and Effect
3. Where do local insects live?	Gather data and evidence (SEP 3) to address the question, Where do local insects live?		SEP 3 – Gather data and evidence DCI – LS2.A: Interdependent Relationships in Ecosystems CCC – Cause and Effect
4.What does my insect eat and what eats my insect?	Analyze and interpret data (SEP 4), then use data as evidence to Engage in argument (SEP 7) to address the scientific question, What does my insect eat and what eats my insect?		SEP 4, SEP 7 – Analyzing/ interpreting/Argument DCI – LS2.A: Interdependent Relationships in Ecosystems CCC – Cause and Effect

roles and assigned tasks. The co-construction process occurs mainly within individual teams, namely Lesson Design, Assessment Design, Learning System, Biology Resources, and Research, with regular check-ins and discussions across the teams. The expertise needed for this phase represents multiple disciplinary areas including STEM educators, learning technology designers, scientists, and classroom teachers.

In our case, the Lesson Design and Assessment teams created the first drafts of 14 lessons, as well as coordinated formative and summative assessment items and rubrics. The Lesson Design team developed three levels of scaffolds that were subsequently adopted and edited by the Assessment team to be consistent across lessons and formative assessment. The Biology Resources team collaborated with the other teams to articulate students' needs to gather, analyze, and construct solutions associated with addressing a local phenomenon. The biology resources included the ADW Pocket Guide observation tool (see Figure 3). The students used the ADW Pocket Guide for field-based animal identification to guide their outdoor observations of local insects. The end-products from Phase Two included complete drafts of fourteen lesson plans, summative and formative assessment items and rubrics, the data backbone within the Gooru Learning Navigator, and biology resources within the ADW Pocket Guide.

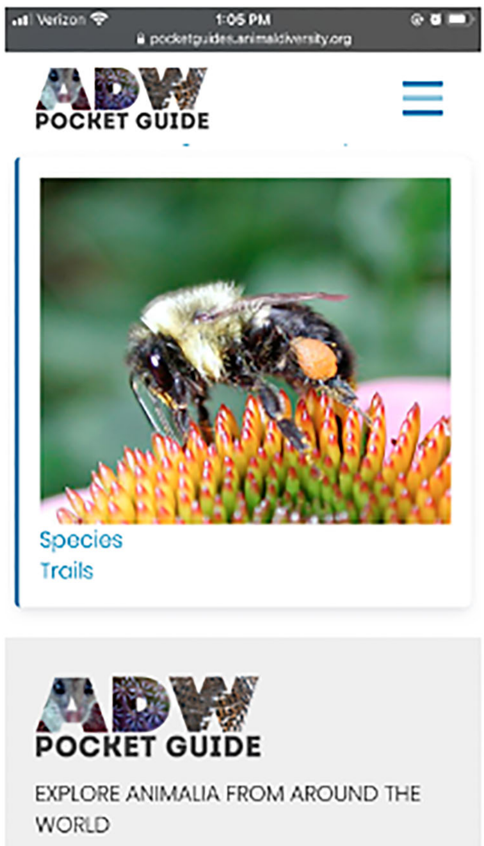

Figure 3. ADW Pocket Guide Observation Tool. The ADW Pocket Guide provides easy access to information on local species, including detailed species accounts with information on their biology.

Phase Three: multi-resource integration

In Phase Three, Multi-Resource Integration, the work consisted of the research team reviewing all instructional materials, including the end products from the previous phases for the purpose of coherent integration of the instructional materials, technologies, and biology resources into the learning management system. The expertise needed for this phase is a STEM educator, a learning technology designer, a scientist, and a classroom teacher.

In our case, Phase Three was primarily led by the Learning Technology Design team. All the teams worked collaboratively to upload and revise the templates, the beta versions of the lesson plans and assessment items into the learning management system called Gooru Learning Navigator (see Figure 4). Our Learning System team worked on the development of the data backbone within the Gooru Learning Navigator. The data backbone consisted of linking formative and summative assessment items to a competency model associated with several learning goal milestones in the curricular unit. In this way, student progress including both time on task and progress towards learning goals, could be reviewed and used to provide feedback by students, the teacher, or the research team. We also linked the biology resources and other external links within the learning management system. Next, we developed professional development materials that provided middle school science teachers with detailed guidance on how to effectively navigate the Gooru Learning Navigator platform and how to use the

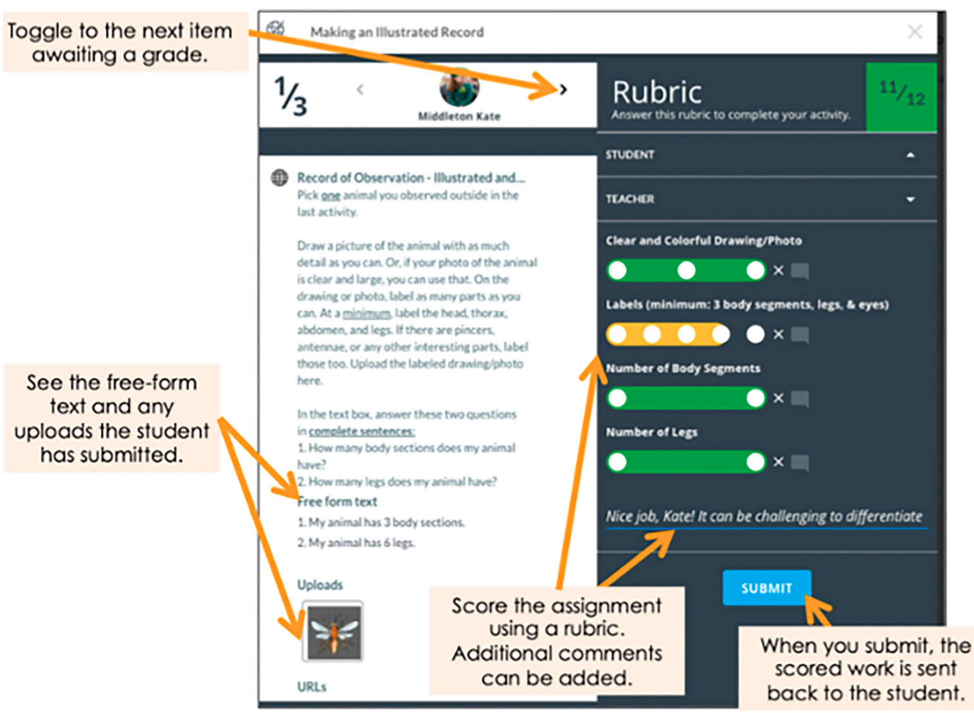

Figure 4. An example rubric within Gooru Learning Navigator where a learner has submitted an answer and supporting artifact of their work for an offline task. The right side illustrates a graded colour-coded rubric. An instructor can also add comments for each component of the rubric.

instructional materials. Phase Three ended with conducting a two-week professional development training course and providing the necessary school supplies for the pilot implementation of the curriculum. The end-products from Phase Three included integrated lesson plans, assessment items and rubrics, biology resources, and professional development materials within the Gooru Learning Navigator.

Phase Four: multimodal implementation

In Phase Four: Multimodal Implementation, the research team tested the co-constructed instructional materials with the target population (i.e. students and teachers) using multiple learning modalities including both synchronous zoom instruction and face-to-face classroom learning. The expertise needed for this phase includes STEM educators and a classroom teacher. An eight-week curricular unit was pilot-tested by a middle school science teacher. The participants involved 18 students from an urban middle school located in the Northeast of the United States. The curriculum was implemented through the Learning Navigator learning platform. As part of the curriculum, students engaged in synchronous and asynchronous activities that emphasised three-dimensional learning, anchoring student learning through local phenomena and design challenges. For example, as part of their eco-solution project, students conducted outdoor observations to learn about invasive species, specifically focusing on a local invasive, the Spotted Lanternfly. Afterwards, they engaged in the engineering design process to create a solution to address the problem of invasive species in their local area. Figure 5 presents an example of a student-created infographic illustrating the proposed solution to the problem of the invasive Spotted Lanternfly.

During implementation, three of our research team members, who were also experts in STEM education, attended the synchronous sessions to provide the teacher and the students with additional support as well as to conduct in-class observations. In addition to the observation notes taken by our research team during each session, we collected other types of qualitative data including weekly teacher reflection notes, various learning artefacts created by the students, and student feedback collected through an anonymous end-of-project survey. The end-products from Phase Four included learner artefacts and qualitative data on the pilot testing of the lesson plans.

Phase Five: analysis & recommendation

Phase Five Analysis & Recommendation involved the examination and evaluation of the outcomes from the implementation and the generation of a list of practical recommendations for revising the instructional materials. The expertise needed for this phase includes STEM Educators and Technology Designers. In our work, we conducted analyses of the qualitative data including in-class observations by the researchers, teacher reflection notes, student-created artefacts, and student feedback. The end-product from Phase Five included a generated list of recommendations to improve the instructional materials, including revisions to the student activities, teacher support activities, biology resources, student assessments, and the interface and delivery of materials and generation of data through the Learning Navigator data backbone.

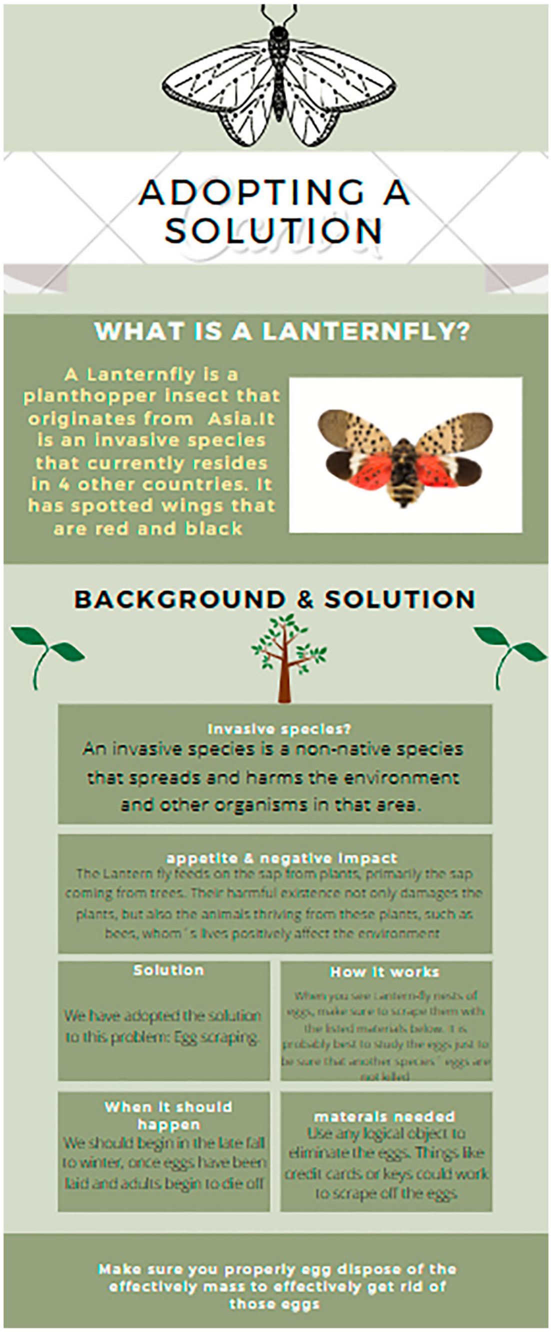

Figure 5. Screenshot of an example eco-solution artifact created by students.

Discussion

This study took a qualitative case study approach to answer the research question, 'What is the process of team co-construction of instructional materials that emphasise learning through both science investigation and engineering design?' Findings from the analysis of two qualitative data sources, namely semi-structured interviews with nine research team members and documentation in form of field notes and learning artefacts, resulted in the proposed five-phase model illustrating the step-by-step process of team co-construction of instructional materials that emphasise learning through both science investigations and engineering design. We learned that multidisciplinary team co-construction process is highly iterative and requires multiple experts of different professional backgrounds at different phases of the co-construction work such as Foundation, Multidisciplinary Construction, Multi-Resource Integration, Multimodal Implementation, and Analysis & Recommendations. As illustrated by our five-phase model, even though the individual team members had specific tasks and roles assigned to them, we found that most of their work was highly collaborative and involved multiple experts often working together at the same time. As shared by Participant A:

> … one of the team members, and later on a small team of others, helped me to figure out what the anchor goals and the competencies were, and together we wrote and revised the curriculum story and the curriculum features tables multiple times. I designed the argument template, but then a whole bunch of people gave us feedback on the format and the scaffolding and that kind of thing. So, I think that everything was a collaborative process …
>
> ..we realized that that we couldn't do all the work we needed to do without co-construction and conversation and influence from the other teams …

Another key lesson learned is that team co-construction work may often include challenges, and it is important to recognise and discuss them openly within the team to be able to address them early on in the co-construction work. As mentioned by Participant B, some of the challenges that our team was able to address early on included '*ensuring coherence across the NGSS anchor goals, individual lesson objectives, and formative and summative assessments*' and 'ensuring *alignment across expertise levels and assigned roles and tasks*'. Another important challenge was ensuring clear communication among team members with different disciplinary backgrounds and levels of expertise. Participant I mentioned that multidisciplinary teams

> need to have enough talk and dialogue between people of different backgrounds and different kinds of expertise that they can actually have a common understanding' and one way to do that is to apply the principle of 'strategic simplification' of the content or topic by the expert 'for a more generic audience or a non-expert to be able to use and work with that information effectively.

Another major challenge that our team had to face was imposed by the COVID-19 pandemic where we had to shift the team co-construction process to a fully remote format. As reflected in Phase Two: Multi-Resource Integration and Phase Three: Multimodal Implementation of our five-phase model of team co-construction of instructional materials, this shift caused us to rethink our instructional materials and activates and plan for kinds of personalised and adaptive products and collaborations that would be more suitable for remote teaching and learning. As shared by Participant A:

> … one of the takeaways is that teams need to consciously think about co-construction and the kind of products that we need for remote classrooms or for fostering new kinds of science and investigation and engineering design … And even after the global pandemic is over, I think we're still going to be doing more of these kinds of things where individual learners are not all doing the same thing at the same time. And delivery doesn't look

> identical in real time for all kids but it's more of an interactive experience between the instructional materials and the teacher. That's not necessarily the same for every kid. So, the more we can think about how construction of materials can really get us to that product and the more we learn about co-construction, the better we are at getting at the products we're going to need in the future.

Our co-construction process is in alignment with our conceptual framework including situated learning approach (Holland & Lave, 2009; Lave & Wenger, 1991; Pellegrino, 2020; Rogoff et al., 2007) and our learning approach, Eco-solutioning (Songer & Ibarrola Recalde, 2021). As mentioned earlier, in Eco-solutioning, students start with learning about local science content through the science practices and deepen their learning of science content through the engineering practice of designing a solution to address a local environmental issue. As shared by our study participants, the co-designed Eco-solutioning instructional materials situated learner activities in meaningful social experiences that facilitated differential engagement with the content when learning through the science versus the engineering practices. The instructional materials also supported students' active knowledge sharing. This approach aligns with similar studies emphasising the importance of integrating engineering design process in STEM curricula (Galoyan et al., 2022; Guzey et al., 2019; McGowan et al., 2017). As shared by Participant G:

> So, the curriculum is designed around two large investigations, one of which is making observations, collecting information about different insects, and learning about them. And the second investigation is more of a design thinking process where the students go through the design cycle, starting with defining a problem that they want to address, and then they brainstorm solutions and then start working on a specific solution to address a problem related to a specific insect species.

This study is significant since researchers and practitioners can build from our work and use the proposed model as a conceptual lens to explore and implement other examples of cross-discipline team co-construction of activities situated in the context of science learning. In particular, our model enhances understanding of how teams collaborate across expertise type and activity to realise a suite of instructional materials that foster learning through both science investigation and engineering design. This study addresses a need to explore new forms of partnerships and to articulate how researchers can productively find common ground, share expertise, and collaborate to facilitate an investigation and engineering design-rich teaching and learning process.

Note

1. Three-dimensional (3D) learning incorporates three key elements: Science and Engineering Practices (SEPs), Disciplinary Core Ideas (DCIs), and Crosscutting Concepts (CCCs) (see Penuel & Reiser 2018) for further explanation.

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