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Research Article

An analytic framework for understanding student thinking in STEM contexts

David Slavit[1], Kristin Lesseig[2] and Amber Simpson[3]

[1]*Washington State University, Vancouver, United States (ORCID: 0000-0003-0236-5161)*
[2]*Washington State University, Vancouver, United States (ORCID: 0000-0001-6019-4386)*
[3]*Binghamton University, United States (ORCID: 0000-0001-5467-4885)*

The goal of this paper is to share an analytic framework for understanding Students' Ways of Thinking (SWoT) in STEM-rich learning environments. Before revealing our refined coding framework, we detail the nature of our collaborations and the various analytic decisions that led to its formation. These collaborations supported our collective ability to make sense of SWoT and produce a more coherent perspective that can be operationalized in STEM contexts. Our analytic framework foregrounds student claim-making and the related evidence and reasoning used in support. Specific commentary about the development and application of each coding category is provided, including examples of student data and rationale for related coding decisions. Our analytic framework, and discussion of its formation, can help educators, curriculum makers, and policymakers make use of SWoT in the development of meaningful and effective STEM education.

Keywords: STEM education; Student thinking; Integrated STEM; Analytic methods; Coding

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1. Introduction

Curriculum and instruction associated with the label of "STEM" (Science, Technology, Engineering, Mathematics) has an established history of approximately 20 years. Early origins of integrated STEM[1] can be traced to National Science Foundation (NSF) initiatives to promote and support transdisciplinary research and instructional practices (Breiner et al., 2012). STEM has been known by many names, has many different meanings (Holmlund et al., 2018; NSTA, 2020), and has faced many criticisms (McComas & Burgin, 2020; Moon & Singer, 2012; Zeidler, 2016).

[1]From this point on, "STEM" refers to "transdisciplinary STEM." While much can be written about the nature of transdisciplinary STEM, English (2016) describes multidisciplinary approaches to STEM education as using content-based contextual themes as the integrating vehicle, whereas interdisciplinary approaches utilize STEM disciplinary content and practices in a more coherent and emergent manner. Our perspective on transdisciplinary STEM is in line with the latter description.

Address of Corresponding Author

David Slavit, PhD, College of Education, Washington State University, Vancouver Campus VUB 330, Vancouver, WA 98686-9600, United States.

dslavit@wsu.edu

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However, the notion of STEM as an entity, and the perceived importance of STEM education, persists. This has been due, in part, to a variety of educational, political, and societal forces over the past two decades.

In 2012, the first author attended an NSF presentation during which Janice Earle, a program director, stated that, "The current climate is a perfect storm for STEM education." Specifically, this storm emerged from supporters of STEM education sharing one of two perspectives, both of which were grounded in the contextual forces previously mentioned. First, proponents of STEM education have sought to maintain technological and economic competitiveness in STEM-related areas (Okrent & Burke, 2021). This perspective is based on capitalism and the advancement of STEM-based industries. Second, proponents of STEM education have sought to develop an informed citizenry that is knowledgeable and fluent in STEM disciplinary knowledge and practices. This perspective is based on democratic ideals and issues of equity (Calabrese Barton et al., 2013; Garibay, 2015).

Given its varied roots and perspectives, it is not surprising that there is not a singular conception or succinct definition of STEM education. Some progress toward this has occurred within the STEM school movement, with consensus building over the past decade around key features of a STEM-based school (Bybee, 2013; LaForce et al., 2016; Martín-Páez et al., 2019; Peters-Burton et al., 2014; Roehrig et al., 2012; Takeuchi et al., 2020). For example, Lynch et al. (2013) identified several "critical components" of a STEM school that include project-based learning and assessment, STEM disciplinary and transdisciplinary foci, in- and out-of-school learning environments, partnerships with external STEM stakeholders, well-prepared and supported faculty and administration, and ubiquitous technology.

In addition to the expansion of STEM schools, STEM education has become a focus of both out-of-school activities, such as afterschool programs and summer camps, and in-school activities, such as classes that integrate aspects of making and tinkering. These activities provide opportunities for hands-on engagement in STEM practices and complement the learning of STEM concepts embedded in state math, science, engineering, and technology standards (Allen et al., 2019; 2020). STEM education is now normally associated with integrated, concept-based content that is developed via extended, active student learning experiences involving materials and technology.

Hence, prior research has delineated general characteristics of the environment that may open opportunities for students to engage in integrated STEM ways of thinking. However, there remains a limited research base as to how to analyze and describe student thinking in these contexts. Such information would help us understand the potential for learning in these settings, aiding those who design and facilitate STEM learning experiences.

2. Frameworks

2.1. Theoretical Framework

As we are interested in understanding student thinking in collaborative settings, we draw on principles of social constructivism (Bruner, 1990; Vygotsky, 1978) to guide our work. We view thinking as both an internal and co-constructed activity mediated by language and other representations. Language has been a particularly important mediating tool in the STEM disciplines (Erath et al., 2021; Kazemi et al., 2021; Lemke, 1990; Pimm 1987). We view language as both a means and resource for learning in individual STEM disciplinary contexts (Erath et al., 2021), which we further assert generalizes to STEM learning contexts, particularly those steeped in student collaboration.

We also draw on the argumentation literature to understand how students use evidence and reasoning to co-construct STEM-based arguments. Constructing arguments is fundamental to generating and establishing knowledge in each of the STEM disciplines. More importantly, argumentation, viewed as a sense-making process, plays a critical role in learning (Kazemi et al., 2021). Individual and collaborative efforts to generate and defend claims about how or why a proposed solution "makes sense" in the context of the STEM activity both deepen and reveal students' conceptual understandings.

Finally, we draw on the emergent theoretical literature related to STEM thinking, particularly those grounded in engineering contexts that most closely align with the CER framework and related work on argumentation. For example, various authors have utilized the notion of evidence-based reasoning (EBR) to discuss how students explore problems in engineering contexts. Most of these authors have focused on the nature of student claims and the associated disciplinary knowledge used to substantiate their claims (Crismond & Adams, 2012; Siverling et al., 2019). Worsley and Blikstein (2016), also working in engineering contexts, have refined this perspective to include four distinct types of EBR: materials-based, example-based, principle-based, and unexplained. Materials-based reasoning occurs when physical objects lead students to generate new design ideas or revise their thinking, such as the use of rubber tubes when making a mock roller coaster. Example-based reasoning occurs when students draw on their real-world experiences to support the modeling or design of a similar object. Principle-based reasoning draws on disciplinary knowledge and practices to support the claim and reasoning processes. And finally, unexplained reasoning is associated with moments of insight or creativity wherein the origin of the reasoning is hidden or attributed to intuition. Our theoretical notion of SWoT, which we describe next, focuses on student claim making and draws on all of the above perspectives.

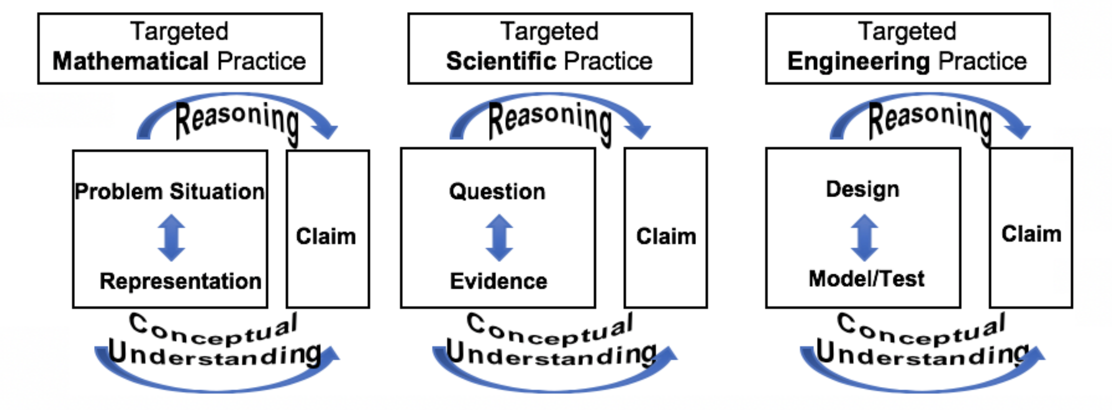
2.2. SWoT

Our notion of SWoT, more fully articulated elsewhere (Slavit et al., 2019, 2021), targets disciplinary and transdisciplinary aspects of claim making. Drawing from McNeill & Krajcik (2012), we extend the CER framework, based in science, to also incorporate mathematics and engineering[2]. While we discussed and made use of other frameworks, we chose CER for its explicit focus on the claim-making process and for its allowance of post-event, naturalistic observation in the analysis. While we also draw on aspects of Toulmin (1958) with respect to the claim-making process, our focus differs in that we are less interested in the quality of the claim. Rather, our goal is to unpack how (or if) students draw on disciplinary content and reasoning processes to make sense of a situation and advance toward a solution or goal. Figure 1 illustrates how we conceive claim-making processes across the disciplines, including the presence of similarities and differences in each disciplinary context. However, despite important differences such as epistemology and disciplinary language (Herschbach, 2011; Reynante et al., 2020), we view the claim-making process as a potential construct with which SWoT in transdisciplinary STEM contexts can be coherently viewed.

As Figure 1 illustrates, disciplinary claims utilize conceptual understanding and reasoning that help define the discipline. These similarities provide a promising path to conceptualizing and analyzing claims, and therefore SWoT, in STEM-rich contexts. However, the differing nature of epistemologies and practices across the disciplines presents challenges to such an undertaking. For example, mathematical claims might be based on inductive reasoning but are generally supported by deductive reasoning grounded in established theorems and definitions. Scientific claims generally emerge from naturalistic observations and are tested against the best available evidence. Engineering claims generally involve establishing a most appropriate model for a given problem or context. Further, from an ontological perspective, engineering claims are generally most tentative, whereas mathematical claims are generally most certain.

[2] While we acknowledge the presence of student learning frameworks in technology education, particularly around the notion of computational thinking, we have yet to incorporate this discipline into our SWoT framework. This is due to our current inability to develop an appropriate CER framework in this area, and a general lack of computational thinking in our data. We acknowledge this limitation and continue to seek enhancement.

Figure 1
Disciplinary ways of thinking; using reasoning to make claims in mathematics, science, and engineering



Our analysis suggests that SWoT in STEM contexts is highly dependent on the established norms and practices of each individual discipline, the context and nature of the activity, the instructional influences on the activity, and the internal and external epistemological forces that drive student thought. By placing student claim making at the center of our analytic framework, we are able to analyze SWoT in a manner that makes use of the disciplinary similarities involved in student thinking, while also accounting for differences across the disciplines. This has led to a coherent framework for understanding the nature of the student thinking present. We now describe the specific aspects of our analytic framework, including a discussion of its origins and ongoing development.

3. An Analytic Framework for Understanding SWoT in STEM Contexts

3.1. Methodology: Developing the SWoT Analytic Framework

3.1.1. Nature of videotaped student learning experiences

All three authors participated in coding STEM-focused student thinking in different research settings prior to our current collaborative work. These included work with STEM teachers to support interdisciplinary learning (Slavit et al., 2016; Lesseig et al., 2017; Slavit & deVincenzi, 2019), professional development focused on argumentation (Lesseig, 2016; Staples & Lesseig, 2020), and out-of-school STEM learning experiences (Simpson et al., 2019; Simpson et al., 2020; Simpson et al., 2021).

Our current collaboration includes analyzing videotaped data and designing a coding framework. Most of the videotaped segments we have analyzed have involved small group student work, but in some cases the students collaborated with a parent or sibling in their home environment. Our collection of over 30 videotaped segments came from K-12 classrooms and after-school settings across the K-12 spectrum. They ranged in length from 10-40 minutes, but usually involved between 15-25 minutes of student collaboration. Our current analysis has focused on approximately ten of these videos, with most segments involving engineering design activities, but videotaped segments from mathematics and science classrooms have also been analyzed and discussed. All videotaped segments were recorded by one of the authors who provided contextual information on the setting and participants as appropriate.

3.1.2. Development of the coding process

We began with the research question, "What is the nature of student thinking in STEM-focused learning environments?" While we were addressing some form of this question in various other research settings and collaborations, we eventually joined together to collectively analyze data. After sharing past experiences and exploring various perspectives on student learning and disciplinary ways of thinking, the authors adopted the SWoT theoretical framework as the primary lens through which to view student thinking, particularly for its focus on the claim-making process.

To begin our coding process, each author individually coded a videotaped segment and shared their codes. During individual coding, each coder also flagged particularly troublesome coding decisions and noted the nature of the questions they asked themselves while making coding decisions. After individually reviewing and comparing codes, we met to discuss similarities and differences across coders and address the questions that surfaced during our individual coding, as well as other issues that emerged during our discussion. As our collective analysis unfolded, we created analytic memos to record coding decisions, which later helped us develop a more complete and focused coding framework. Throughout this time, coding rules were identified and debated. For example, in addition to creating the specific codes and coding levels, we discussed which codes were always or rarely applicable, which were dichotomous, and how to address issues of multiple, quick claims made in successive order over a short period of time. While some of these dilemmas remain unresolved, we were able to collaboratively decide on a coding process for many of these important issues. For example, for simplicity and a more accurate representation of the student claim-making activity, we agreed that a short sequence of related claims would be coded as a single claim.

Several aspects of the CER framework were explored in great detail. For example, we debated on whether to consider reasoning as a two-dimensional structure, with global codes relating to the larger argument structure that defined the overall interaction and local codes relating to the specific nature of the reasoning employed. We eventually decided to not enact the global code, feeling that our simultaneous coding of claim-evidence-reasoning provided adequate information at a global level. We also spent time considering the manner in which students employed evidence, as evidence can be employed before, during, or after the claim. We decided to make this temporal aspect a specific dimension of our coding process. We also continued to note when reasoning or evidence was applied multiple times to a single claim. The role of language played a significant role throughout our deliberations and became a distinguishing factor between formal and informal claim making and reasoning, as well as the tentative or certain nature of the claim.

The role of the context presented a significant dilemma and challenge to our coding process. As previously mentioned, for each videotaped segment, one of the authors had specific insight into the learning environment and participants. This provided some level of insider knowledge to support coding decisions. However, while this enhanced our own contextual perspective, it became apparent that this did not resolve a more complex issue that involved the following question: From whose perspective should the code be made? Our choice consisted of utilizing our perceived understanding of the learners' perspectives, our own understanding of the context, and/or the nature of the discipline and disciplinary thinking being enacted. In many instances, each of these lenses might produce different coding decisions. To resolve this issue, we drew from Cobb et al.'s (2009) analytic framework related to student identity. While not drawing from this framework in an isomorphic manner, we applied their general construct of simultaneously considering established disciplinary norms and practices with those in the local learning context. Cobb et al.'s (2009) notions of personal and normative identity reflect these two different contextual perspectives. Similarly, we attempted to interpret comments related to claims, evidence, and reasoning from the perspective of the learner, while also drawing on our own understanding of accepted STEM disciplinary practices. This supported our ability to have a common lens on what constituted a disciplinary claim or categorize a type of reasoning, but still provided a means of incorporating our perceived intent of the learner. The age of the learner and their perceived ability to fully articulate their meaning also played roles in our coding decisions. As mentioned previously, the role of language and students' perceived ability to articulate their ideas had a significant influence on our coding decisions regarding the formal nature of the claim or reasoning.

Overall, our analytic conversations focused on details of the CER framework and how these argumentation practices were being enacted by the students in these STEM environments. Early on, *a priori* codes consisted of claim, evidence, and reasoning and a small set of other codes related to topics such as role of instruction/context. Emergent factors of interest included the role of disciplinary content and practices, the tentative or certain nature of the claims, the level of formality throughout the CER process, the timing of the claim, and several other aspects of student thinking we observed and discussed. Eventually, these conversations led to an emerging analytic framework which was translated into a set of categories and rules useful in analyzing student thinking in STEM environments. We share our current coding system in the next section.

3.2. Analytic Coding Framework

Our collaborative analysis produced an analytic framework and coding system, summarized in the following sections. Each code has an accompanying "driving question" to help illustrate our thinking processes enacted when applying each code. Our overall approach was to view videotaped examples of student thinking, identify any student claims that are made, transcribe the specific wording of the claim, or describe the activity that defined the claim, and then apply the set of codes related to claims, evidence, and reasoning.

3.2.1. Claim codes

The first step of the process was the identification of a claim made by a learner. While the identification of a claim can be subjective, we spent considerable time discussing our collective understanding of what constitutes a claim in a STEM-rich learning environment, some of which we discussed in the previous section. While various perspectives can be taken, Toulmin (1958) stated that a claim was a statement put forward publicly for general acceptance. Similarly, we view a claim as the core focus of an argumentation process around which reasoning can be applied to verify or disconfirm the validity of the claim (Gray & Kang, 2014; Lee et al. 2014). A claim involves positioning, and therefore elicits arguments that utilize evidence and reasoning in support of that position. Claims are also set in a context and are dependent on the perspectives of the learner or learners making the claim (Toulmin, 1958; Forman et al., 1998). For example, claim-making in group settings is often a social process, and when there is no rebuttal to an initial claim it can become taken-as-shared (Krummheuer, 1995; Yackel & Cobb, 1996). Once we identified a claim, the precise language used to make the claim was transcribed and documented, as was the time stamp relative to the videotaped segment. While most claims incorporate some degree of language, we have encountered claims that have been solely comprised of gestures or other actions. We coded most of these latter claims as "implicit" unless the gestures or actions showed clearly the precise nature of the learners' claim, which we then would describe using our own interpretive language.

After a claim has been identified, the five codes related to "Claims" were then applied (see Table 1). The first two sets of codes are heavily dependent on the nature and role of the language used to make the claim. We do not discount claims that lack uses of precise disciplinary language, as we understand there are situations where less formal language is more natural, or where learners lack the linguistic ability to make a claim using such language. Our "Explicit/Implicit" and "Formal/Informal" codes were developed to provide description of the ways in which learners expressed their claim with the hope of revealing specific learning contexts that relate to language use in the claim-making action. We have found the "Disciplinary/Transdisciplinary" code to be very important in expanding our conception of SWoT in STEM contexts. However, most of our examples to date have not been coded as transdisciplinary, revealing that the learners we have observed remain embedded in disciplinary ways of thinking when making claims, even when they are engaged in transdisciplinary work. The "Tentative/Certain" code emerged as we inferred learners' positioning towards their claim and wanted to capture this important dimension of student thinking (Lee et al., 2014). Tentative claims can be in the form of declarative statements, but problem posing might be considered a claim as well. The degree of tentativeness can be defined by words, but at times we inferred tentativeness or certainty by the tone of the wording. We also remain curious as to the role of the discipline with respect to the tentative or certain nature of the claim. Finally, the "Novel/Challenge" dimension was added for several reasons, the most important of which was to help capture a related sequence of claims being made. Specifically, this code helps define a structural chain of student claims being made by the students, as a claim coded as challenge tends to follow an associated novel claim, allowing us to link a set of distinct claims together. The Challenge code also allows us to identify instances in which learners might be pressed to elaborate on or introduce new evidence to support a claim, or more explicitly state their reasoning through the use of further warrants (Toulmin, 1958).

Table 1
List and description of codes applied to each claim or claim sequence

Claim (or Claim Sequence)	
C1. Explicit/Implicit *Driving Question:* Is the claim clearly articulated by the claimer?	
Explicit - articulated and understood by at least the speaker, language (with possible accompanying gestures) provides clear meaning of the speaker's intent	***Implicit*** - not fully articulated by any group member, they are defined by the actions taken and the perceived intent of the student or students
We have coded most claims made with gestures as "implicit" unless the gestures or actions showed clearly the precise nature of the learners' claim, which we then would describe using our own interpretive language.	
C2. Formal/Informal *Driving Question:* Does the claim contain academic language and/or is grounded in disciplinary practices and ideas and/or draw on abstract disciplinary contexts?	
Formal - use precise, academic language; the meaning embedded in the claim is grounded in specific disciplinary ideas and practices; abstract disciplinary contexts are used	***Informal*** - use colloquial language; the meaning embedded in the claim is grounded in everyday experiences, personal background, and/or personal experiences
C3. Disciplinary/Transdisciplinary *Driving Question:* Does the claim draw on one or more than one STEM disciplinary ideas and practices?	
Disciplinary - draws on a specific STEM discipline for the claim making process; Draws on a disciplinary way of making claims	***Transdisciplinary*** - draws on a combination of STEM disciplines for the claim making process; Claim invokes multiple disciplinary ways of making claims
If disciplinary code is used, then S, T, E, M are subcodes relative to the identified discipline.	If transdisciplinary code is used, then a <u>*combination*</u> of S, T, E, M subcodes relative to the identified disciplines are added.
C4. Tentative/Certain *Driving Question:* Does the claimer appear sure or unsure about the claim being made?	
Tentative - unsure statement or hunch; Statement made in the form of a question that is ***intended*** to provide information or extend/advance the dialogue	*Certain* - statement made with confidence
Tentative claims can be in the form of declarative statements, but problem posing might be considered a claim as well. The degree of tentativeness can be defined by words, but at times we inferred tentativeness or certainty by the tone of the wording. We also remain curious as to the role of the discipline with respect to the tentative or certain nature of the claim.	
C5. Novel/Challenge *Driving Question:* Does the claim add a new dimension to the activity and discussion?	
Novel Idea - introduces a new idea or problem-solving dimension into the dialogue	*Challenge/Negotiation/Rebuttal* - made in response to a recently-stated claim that offers a different perspective or direct challenge to the initial claim

3.2.2. Evidence codes

Our two levels of evidence codes both have a temporal dimension, but with respect to different aspects of timing related to the claim (see Table 2). The first code includes four specific types of evidence we have identified throughout our work that relate to when the *source* of the evidence emerged. The second evidence code identifies when the evidence was *applied or utilized* with respect to the claim.

Table 2
List and description of Evidence codes

E1. Type of Evidence *Driving Question:* What is the source of the evidence, and when did this evidence occur?				
Fact	*Prior Experience*	*Test case*	*Perception or Observation*	*None, or not able to determine*
Use of a past-learned fact, example, or definition to support the claim (note – the 'fact' doesn't need to be one we would accept as true but one the student(s) seem to accept)	Use of an event that occurred ***before*** the current problem-solving experience to support the claim	Use of a specific and ***recently occurring*** event to support the claim (e.g., verify a solution/rule with a specific case in math or conduct quick test to see if something 'works')	Use of an experience or event that occurred ***during*** the current problem-solving experience; what a student "sees in the moment"	
In line with our general coding perspective, we assume the learners' perspective when identifying facts, inferring that the fact is well-established by the learner prior to the claim. In other words, a fact is taken as established with respect to our perspective of the learners' understanding and development.				

E2. Timing of Evidence *Driving Question:* At what point in the claim making sequence was the evidence utilized to produce and/or support the claim?		
Evidence utilized Prior to the Claim	*Evidence utilized During the Claim*	*Evidence utilized After the Claim*
Note that evidence can be used to produce a claim, support a claim, or both. This code helps delineate these differences.		

Regarding the type of evidence code (E1), the first three types all emerge prior to the claim-making action but differ in their timing and/or nature. "Facts" include disciplinary knowledge and examples that have usually been established well before the claim-making action. In line with our general coding perspective, we assume the learners' perspective when identifying facts, inferring that the fact is well-established by the learner prior to the claim. In other words, a fact is taken as established with respect to our perspective of the learners' understanding and development. "Prior experience" has a similar temporal dimension to facts, as it also assumes the event used to support the claim occurred previously. However, we felt that distinguishing facts and experiences would be important in understanding the nature of student thinking, as well as the impact of the learning context on the evidence used. Finally, "Perception" infers the use of a contemporary phenomenon that occurred simultaneous to the claim-making action. We noted several uses of perception as evidence, most of which relate to explicit, informal, certain, and novel claims.

The second code type related to evidence (E2) involves the timing of the application of the evidence with respect to the claim. While this code is usually in line with the temporal nature of the first evidence code, we identified examples where this nuanced distinction was important to make, and therefore created this second-level evidence code. For example, while a fact might be previously known, it might be applied after the claim has been made. This can occur when the fact was an additional piece of evidence for an already-established claim, or when the fact was used to verify (or further verify) an emergent claim. The latter use of fact as evidence was usually associated with a tentative claim that might then be made more certain by the introduction of the fact at a later time. Because of these possibilities, our coding was modified to address claims for which evidence was presented prior to the claim as well as additional evidence presented after the claim.

3.2.3. Reasoning codes

The third dimension of codes, which are related to reasoning, were also separated into two levels (see Table 3). Reasoning is the means through which claims are supported, and the link between the evidence and the claim. The first-level code for reasoning identifies the explicit or inferred nature of the reasoning used by the learner, which is distinguished by the level of articulation using words and/or actions. The three second-level reasoning codes relate to its experiential or abstract basis, its personal or external source, and its disciplinary or transdisciplinary nature.

Table 3
List and description of Reasoning codes

Reasoning Level 1	
R1. Explicit/Inferred *Driving Question:* Is the reasoning clearly articulated or presented by the learner?	
Explicit	*Inferred*
Reasoning clearly articulated by the claimer with words and/or actions	Reasoning is apparent, but no articulation of the claim using words and/or actions is made by the claimer
Reasoning Level 2	
R2. Experiential/Abstract *Driving Question:* Is the reasoning based on observable evidence or does it draw on theory and/or general properties?	
Experiential	*Abstract*
Reasoning based on observation, physical evidence of specific instances (perhaps more inductive logic)	Reasoning based on theory and/or general properties; (possible attempts at deductive logic)
R3. Personal Authority/External Authority *Driving Question:* Does the claimer rely on their own or others' source of reasoning?	
Personal Authority	*External Authority*
Claimer relies on own reasoning (positions themselves as person in the know)	Claimer draws on external sources for reasoning (claimer relies on perceived knowledgeable other or authoritative text or goal of the task/activity as presented to them by some authority figure)
R4. Disciplinary/Transdisciplinary *Driving Question:* Does the reasoning invoke one, or more than, STEM disciplinary ways of thinking?	
Disciplinary	*Transdisciplinary* [KL2]
Draws on single, specific STEM disciplinary reasoning	Draws on a combination of STEM disciplines in the reasoning process; Reasoning invokes multiple disciplinary ways of thinking
If disciplinary code is used, then S, T, E, M are subcodes relative to the identified discipline	If transdisciplinary code is USED, then a *combination* of S, T, E, M subcodes relative to the identified disciplines are added
For both disciplinary and transdisciplinary reasoning, specific descriptions of the kind of reasoning at play should be added in as much detail as possible after the collection of reasoning codes. This might include phrases such as "spatial reasoning," "analogic reasoning," "finding best design," or "deductive logic." Descriptive statements might also be used.	

The final stage of coding involved qualitative descriptions of the kind of reasoning evidenced in the videotaped segment. Because of the numerous types of reasoning across the STEM disciplines, we attempted to focus on identifying the most common and most generalizable types of reasoning in the description of our codes. While this has limitations, it allowed us to be more focused in our observations and subsequent conversations about the nature of the student reasoning we have identified. We drew on Worsley and Blikstein's (2016) four types of general reasoning codes (Unexplained, Principle-based, Materials-based, Example-based), discussed above, as a starting point in our reasoning descriptions. While Worsley and Bilkstein analyzed student reasoning in engineering contexts, we found this framework to be useful in describing reasoning across the STEM disciplines. We then provided further descriptions using more specific disciplinary or transdisciplinary reasoning, such as spatial, quantitative, cause-effect, analogical, and constraints-based. This list of specific types of reasoning should be considered tentative, and the continued modification of this list lies at the heart of our current work. Further details related to the nature of our codes, and coding decision guidelines, are found below.

4. Examples: Further Issues and Dilemmas

To better illustrate our coding process, and to further address the current issues and dilemmas we are facing, a few examples of codes and coding negotiation will be explored. The first group of issues and dilemmas relate to the initial coding decision of what constitutes a claim. We then discuss a variety of issues and nuanced decisions that emerged throughout our coding process.

4.1. What Constitutes a Claim?

Various conversations emerged in our joint coding analysis regarding the nature of a claim. These included student statements perceived as questions, procedural statements that contained assertions, and the occurrence of successive claims made over a relatively short period of time. Each of these issues was resolved through discussions of specific examples, though coding decisions are always based on the coder's interpretations and assumptions, so a degree of subjectivity remains. We provide examples and discussion for each of these three coding decisions.

4.1.1. When is a question a claim?

When engaged in collaborative learning, students often ask questions of each other. We observed key differences in the nature of these student questions which had important implications on our coding process. Specifically, we identified student questions that were not further investigated or articulated and, while being a genuine curiosity, were not perceived to be intended to engage the students in further thinking. We decided to not code these questions as claims. For example, while attaching light sensors to a rain gauge, a young boy asked, "Should we use tape or glue?" We agreed this was not a claim, but more of a procedural dilemma.

However, if in the view of the coder the student question contained *substantive* commentary *intended* to advance the dialogue through the question, then it was labeled as a claim. Nearly all such claims were labeled as tentative. This coding decision was made partly based on our intent to cast a wide net on claims, but to also allow these kinds of explicitly tentative statements to be captured in our analysis. For example, two students who were building a mock roller coaster using a series of foam tunnels encountered places where the marble got stuck:

> Student A: It gets stuck, and then it goes back and gets stuck here. Can I put it (the marble) here and it will go? No …
>
> Student B: It needs more power.

While Student A asks a question, we coded this as a claim as it provided specific information that addressed the activity and was perceived to advance the current discussion. We viewed this particular question as a tentative claim about the viability of the current design. Most student questions were not coded as claims as they usually did not contain specific information, but instead were requests for information or guidance. However, claims in the form of questions were important to code as they provided direct evidence of the tentative nature of student thinking in various contexts.

4.1.2. When is a procedural statement a claim?

A relatively common coding dilemma involved decisions as to the disciplinary level to which a given statement had to rise in order for it to be considered a claim. In other words, how should we address claims that had little significant disciplinary value? Multiple instances were found where students would discuss relatively low-level aspects of the STEM activity, many of which involved statements of procedure or delineating the next step in an activity. For example, while programming a robot to follow a premade path on the floor, students made comments such as, "We should move chairs out if doesn't fit" and "We should start moving forward because we only have 4 minutes left." While these assertions do address the engineering design aspects of the activity, we did not feel they rose to the level of claim as the first did not contain significant disciplinary content, while the second was purely procedural in nature and did not contain any disciplinary content at all.

4.1.3. When is a sequence of claims a single claim?

In the course of collaborative student activity, there are long periods of time where no student claim is made, but there are also times where a significant number of student claims are made over a relatively short period of time. Our discussions centered on how different in *nature* and in *substance* the claims were. While this decision remains subjective and influenced by our perceptions of the learners and learning context, we agreed that a claim needed to be qualitatively different in nature and substance to constitute a new claim. Differences in the nature of the evidence on which the claim was based also played a role in the coding decision. When these differences did not exist across the claims, we saw the successive claims as a chain that constituted a larger, single claim. In these instances, student claims inside the chain can be repetitive, generative of each other, or different in nature. In the case of repetition, no new codes were made, and the original claimer was given credit for the claim (i.e., the repetitive claim was ignored).

When successive claims were different in nature from the first related claim, two separate codes were made, but the codes and related evidence/reasoning codes were all maintained inside a single claim sequence. The initial claim was usually labeled "Novel" while the second claim was usually labeled as "Challenge." For example:

> Student A: Still, I think this part is blocking it [points to a piece of the foam, then takes off tape and tapes another part of the foam]. I have a good idea. Tape it here [points to another piece of the foam]. And then we could tape it on here like this. [Student takes several seconds to place tape on the foam track] Two pieces of tape supporting one.

We viewed the first sentence to be a claim related to the engineering design, and the subsequent statements providing a challenge to the students' original claim, as it offered a new way of conceiving the design as well as how to tape the structure. While it was far more common for a claim to be challenged by someone other than the claimer, we present this example to illustrate when a single student can challenge his own initial claim.

Finally, we spent considerable time discussing how to code the case of generative claims, which built on successive ideas. For example, two high school boys were trying to flip a die lying on the floor using a robotic arm they designed and built. As one operated the arm, the other provided guidance:

> Student A: Bring it lower.
> Student B: Go. Wait.
> [Robotic arm is too high to grab the die, and misses it]
> Student A: Sorry, that was my bad. Bring it out. I can't do anything with that.
> Student B: Go.
> Student A: Nice.
> Student B: Now you gotta bring it up. Yeah!

> [Robot arm grabs die and flips it]
> Student B: Oh, that was good.

This successive set of statements constituted a single claim in our view as they were generative in nature. The claim was disciplinary (engineering) and addressed the validity of the students' design and test case. The series of statements outlined the process of the test case, so in some way they were procedural, but they rose to the level of a claim as they were specific assertions that produced evidence and required verification through reasoning. They were a single claim because each specific statement built on the prior statements, and taken as a whole they produced a singular, engineering-based claim that the robotic arm is capable of flipping the die.

4.2. Other Coding Issues: Disciplinary Knowledge, Practices, and Reasoning

As stated above, we viewed a claim as an assertion that contained a level of disciplinary substance. The level of disciplinary knowledge or practice required to constitute a claim was much debated, and analyses of specific examples of disciplinary and transdisciplinary thinking were very important in resolving this coding dilemma. We present three specific coding dilemmas encountered in this realm, with discussions of our resolutions through examples.

4.2.1. What is disciplinary and transdisciplinary reasoning?

After much analysis and debate, we decided eventually to not establish codes for specific types of disciplinary reasoning, but instead to document examples and descriptions of such reasoning as they emerged. This decision was due to the large number of kinds of reasoning that exist across the disciplines, and the impracticality of developing a predetermined framework and set of codes for each one. We also made specific efforts to explain why we coded thinking as transdisciplinary when this arose, and to describe its nature in as much detail as possible.

Most of the dilemmas we encountered in this area were based on differences in epistemology and practice across the disciplines. For example, visual and spatial reasoning were common types of reasoning employed by students during the claim-making process. While these have specific roots and meanings in mathematics education (Battista, 1990; Clements & Battista, 1992; Rasmussen & Bisanz, 2005), they can also be applied in science, engineering, and transdisciplinary settings (e.g., Hsi et al., 1997). In engineering situations, test/retest disciplinary practices arose frequently, as did reasoning based on a *best* design. We have commented elsewhere on the tendency for formal disciplinary reasoning in STEM learning contexts to arise only after the instructional leader or context makes specific suggestions for their use (Slavit et al., 2021). However, when this happened, students employed a variety of types of disciplinary reasoning which we attempted to label and describe.

The type of evidence associated with the claim also impacted coding decisions. For example, observation plays a large role in the scientific process and is an established practice. We debated the degree to which a claim based on observational evidence in science is formal, particularly when a mathematical claim based on observation can be problematic, as it can lead to overgeneralization and a lack of deductive reasoning. As stated earlier, we drew on accepted disciplinary practices for support in our coding decisions, allowing needed flexibility to enact different kinds of coding decisions across disciplinary learning contexts. Hence, observation as evidence was much more likely to lead to formal scientific claims than to formal mathematical claims.

Examples of transdisciplinary claims were less common than disciplinary claims, as students tended to stay inside disciplinary siloes when thinking about specific aspects of the overall STEM task. However, examples of transdisciplinary claims did emerge, particularly when informal claims were made. For example, at the very beginning of the roller coaster activity, the following dialogue occurred:

> Student A: We have all this space to ourselves [referring to the wall where they will tape their foam tubes to create a mock roller coaster]. We should start it over here, so I can put one end over here.

> I'm just keeping this here [holds piece of foam tube to the wall]. Then it should be angled downward to give it more energy.
>
> Student B: Ok, you hold it there and I'll do the tape." [grabs one end of the foam tube]

Here we see an initial engineering-based claim related to the space needed for the overall design. While visual thinking is part of this reasoning, we see the claim as grounded in the single discipline of engineering. However, we see the final three sentences of Student A as a transdisciplinary claim sequence about the precise nature of the design that involves the disciplines of engineering and science. The use of spatial sense and the term "angled" suggest mathematical reasoning was also at play to some degree. The explicit use of the term "energy" and associated scientific properties make this claim formal in nature. We determined that the nature of the evidence was Past Experience that was applied during the claim, as we assumed Student A had past experiences with roller coasters or other objects that fell due to gravity. However, we also felt that the evidence could be coded as Fact, given that the student might be applying more abstract notions of gravity and energy in this reasoning.

4.2.2. Can disciplinary practices constitute claims?

Various perspectives on disciplinary practices exist, including specific descriptions in leading mathematics (National Governors Association, 2010) and science/engineering (NGSS Lead States, 2013) frameworks. Our working definition of a disciplinary practice was what we would expect of a scientist, engineer, or mathematician while engaged in the observed STEM activity. We found several examples where the distinction between a disciplinary practice and a claim was blurred. For example, in the rain gauge activity, a boy worked with his mother to insert LED lights at each gradient of the gauge. After testing the colored lights, the following dialogue occurred:

> Boy: I didn't test the clear ones.
>
> Mother: Should we test them real fast?
>
> Boy: Yes.

The engineering practice of testing became the impetus for this claim. However, the claim was coded as interdisciplinary due to the scientific notions of electricity and circuitry that were also present in this part of the activity. In general, we found numerous instances where disciplinary practices gave rise to, and even helped constitute, a claim.

4.2.3. Should reasoning be coded if it is not made "Visible?"

When students construct understandings of STEM ideas and situations, they communicate about a variety of things. Unfortunately, they enact little communication about the nature of their reasoning. While we heard a few statements such as "We have to do this because …," explicit statements made by students about their reasoning were not common. Therefore, many of the codes related to reasoning were Implicit. Further, whenever evidence was coded as Not Able to Determine, reasoning was almost always coded as Implicit. Therefore, while reasoning was not always made explicit by students, we were sometimes able to provide a code to help describe the nature of the reasoning we perceived.

5. Conclusion and Implications

The primary goal of this paper is to share an analytic framework for understanding SWoT in STEM-rich learning environments. In this paper, we have presented not only our refined coding framework, but have also detailed our collective work to establish meaningful, mutual understandings of how the CER framework can support an analysis of student thinking in STEM contexts. Our collaborations supported our collective ability to make sense of SWoT and produce a more coherent perspective that can be operationalized in STEM contexts. We see the most valuable part of our work to be the discussions we have had surrounding our coding questions and wonderings. We reiterate that others might make different decisions, but our coding framework, and description of how we operationalized it, might serve as a guide for others so they can have similarly productive discussions. We see the specific value of our work to be a lens and analytic framework researchers can use to make sense of SWoT, but to also potentially modify for their own purposes and contexts. We anticipate our own modifications as our analysis continues to unfold.

Our framework supports researchers' and educator's efforts to identify and describe SWoT in STEM-rich learning environments. Given the dearth of available theoretical and analytic frameworks for this kind of research (Li et al., 2019), we see value in this contribution to the advancement of research on student thinking and learning in STEM contexts. Our framework includes descriptions of what constitutes a claim, the first step in our coding process. However, more nuanced aspects of student claim making, including its tentative or formal nature, can be laid bare using our framework. Our framework also provides opportunities for open coding of types of reasoning, while supporting specific ways of connecting reasoning to both claims and evidence. The latter includes attention to when evidence both arises and is applied by the student, and how this might impact the overall CER process. Analyses that support connections across the individual STEM epistemologies and ways of thinking adds depth to our current understanding of transdisciplinary teaching and learning (Takeuchi et al., 2020).

We also see our framework as a useful support for STEM teacher educators. Most mathematics and science methods and other education courses remained siloed, with limited integration across disciplinary content and pedagogic lines. Because pedagogy courses draw on theoretical grounding for how students think, our framework provides an avenue for mathematics and science educators to draw on similar perspectives when exploring connections between student thinking and classroom instruction (Kazemi et al., 2021). By focusing on the nature of claims made by students, as well as the accompanying evidence and reasoning, pedagogy courses (particularly content methods course courses) and professional development experiences can be integrated more readily. Such integration could provide much needed opportunities for future and practicing teachers to engage in targeted discussions of disciplinary and transdisciplinary STEM classroom practice.

Finally, we see the framework as useful in capturing transdisciplinary thinking whenever it might occur and in providing evidence of potential differences in SWoT across disciplinary contexts and practices. Unfortunately, our data corpus has yet to provide a significant number of examples of transdisciplinary thinking. In our video analysis to date, students' moment-to-moment disciplinary practices have remained mostly siloed, with infrequent instances of claim making that transcends disciplines and utilizes transdisciplinary reasoning. We are hopeful that our work will reveal more examples of transdisciplinary thinking, and hope that others might make use of our framework in attempts to further our understanding of this kind of SWoT (Kelley & Knowles, 2016; Moore et al., 2020; Takeuchi et al., 2020). Such information would be valuable to educators, curriculum makers, and policymakers interested in building on current SWoT in support of more meaningful and effective STEM education.

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