STEM Language can be the Stem of the Problem

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***Abstract*—Engineering collaboration requires successful interdisciplinary communication between professionals who have highly specialized, content specific vocabularies. STEM language research has shown that people encounter barriers to communication due to different understandings of particular words. Additionally, linguistics research has shown that confusion over specific words can be due to many causes such as alternate meanings or senses associated with that word. However, very little research has studied interdisciplinary task collaboration within a linguistics-based framework. This study identified and categorized patterns of words and phrases that caused confusion during an engineering task at a STEM summer camp for secondary teachers. The results demonstrated that confusion over meanings of words inhibited the participants' progress toward completing the task. When two participants had a common or shared vocabulary, they were able to negotiate meaning, resulting in greater success on the task.**

Keywords—Language, Interdisciplinary Collaboration, Communication, STEM Vocabulary, Linguistics

I. Introduction

It is estimated that over 1,000 words are created in the English language each year [1]. New words are created in various ways to accomplish various purposes. However, in general, words are created to explain or express new knowledge, ideas, and phenomena that are discovered and that occur in our ever changing intellectual and physical worlds; this impetus for generating new words lies at the center of science, technology, engineering, and mathematics (STEM) fields and there it will remain.

Languages and their words are in a constant state of transition, during which new meanings are attributed to words with previously existing meanings. Examples of this phenomenon include the now multiple meaning word tweet, in which one meaning describes the onomatopoeic sound of a bird, and another, the act of posting on the social media platform, Twitter. This phenomenon is of particular relevance in STEM fields in which individuals have given new technology, innovation, and discoveries the nomenclature of already existing words. The fields of computer science and engineering are rife with creative word formations that have incorporated existing words and meanings. For example, imagine the initial confusion students may experience on hearing that they will be learning basic programming using Raspberry Pi. With no previous experience with the phrase Raspberry Pi in this context, the instance provides a highly unique and confusing image entirely unrelated to the computer to which the name refers. The wordplay inherent in the name Raspberry Pi presents merely a cursory glance into the number of words formed through this pattern. This is only one of a myriad number of ways that words may take multiple meanings. It is essential to the success of students engaging in STEM fields for educators to further examine and address instances of multiple meanings that can occur in interdisciplinary STEM vocabulary and to prepare their students to successfully navigate within the academic contexts where these words occur. However, students' successful interdisciplinary navigation of STEM vocabulary is highly contingent on that of their teachers, who must themselves be prepared and equipped with tools to understand contextualized vocabulary outside of their subject domain. If instructors exhibit inhibited interdisciplinary understanding of STEM vocabulary, they will be unable to proficiently impart the skills and knowledge required to develop a fluid and comprehensive vocabulary knowledge to their students.

II. Relevant Literature

There has been a drive in recent decades to create rigorous standards for the improvement of students' vocabulary knowledge. Advocates of this movement believe that explicit instruction of vocabulary words and strategies for understanding meanings of new words will help improve students' vocabulary knowledge [2-4]. Several researchers have emphasized this need for intensive vocabulary instruction specifically within STEM disciplines [5]. This need for explicit and guided instruction is vital to a students' success as vocabulary becomes more technical, complex, abstract, and dense as students proceed through their academic career [6], [7]. Academic disciplines each contain their own set of specialized, content-specific vocabulary; however, these vocabularies are not discrete, separate entities, but rather frequently interdependent and intersecting [8]. The amalgamating process that occurs when these seemingly context-specific vocabularies intersect may occasionally cause confusion as the meanings of a particular word may differ between disciplines [8]. In the same way that teachers provide students with the knowledge and tools to navigate their own disciplines, they must be equipped to guide students through negotiating meaning in an interdisciplinary context.

The ability to differentiate between the various meanings of words is essential at the intersection of STEM fields. Finding effective and innovative solutions for current issues requires that 21st century engineers and scientists be team members "who thrive while working with a variety of people having differing social, educational, and technical skills"([9], p.8). This form of collaboration requires both written and oral communication skills in utilizing and comprehending interdisciplinary vocabulary. Researchers have determined that students' ability to understand science [10] and mathematics [11, 12] concepts is in part predicated on their ability to identify and accurately comprehend relevant vocabulary [13] situated within a particular STEM-related context. Acquiring this level of vocabulary knowledge is an essential factor in improving students' performance [14]. Results from previous studies indicate that students' collaboration on interdisciplinary STEM projects was more successful when they used and mutually understood one another's terminological vocabulary during the project [8]. The ability to comprehend and utilize formal vocabulary terminology has also been shown to drastically improve the preciseness of students' communication as their semantic understandings of both unknown and familiar words expanded [8], [15]. Similar results have been found for middle and high school teachers from varying disciplines who engaged in interdisciplinary STEM activities: those with a common interdisciplinary and terminological vocabulary were more precise in their communication and therefore experienced greater success in collaboratively completing the interdisciplinary STEM activity [16], [17]. In sum, extensive and flexible understandings of words is necessary to effectively collaborate within an interdisciplinary STEM context.

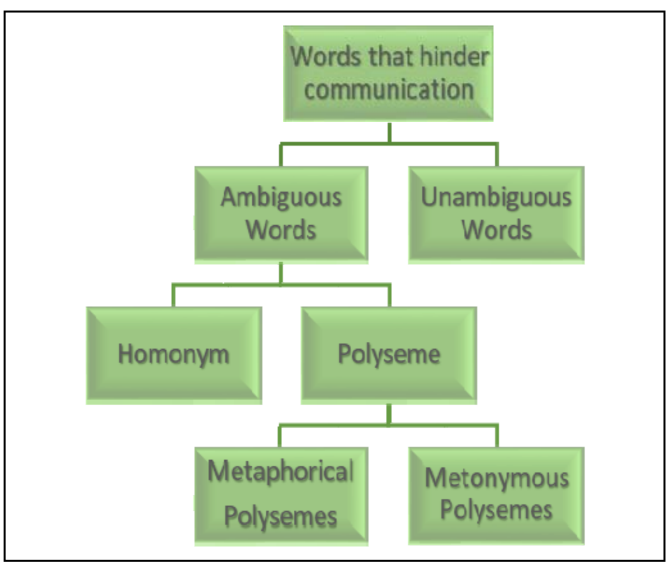

Fig. 1. Model for categorizing words based on linguistics research

TABLE I. GENERAL DEFINITIONS

Category	Definition
Ambiguous Words	Words that have multiple meanings
Homonomys	Words that share a similar form but have distinct, unrelated meanings
Polysemes	Words that share a similar form and closely related meanings
Metaphorical Polysemes	Polysemes that have a literal meaning and a closely related figurative meaning
Metonymical Polysemes	Polysemes whose primary and secondary meanings are literal
Unambiguous Words	Words that have a single meaning

a.

This necessity for a comprehensive and flexible knowledge of STEM vocabulary is largely due to the plethora of words whose meanings are highly dependent on the context in which they are used. For example, students frequently hold a more generalized, everyday understanding of a word that conflicts with the precise and highly contextualized meaning of the word in an academic STEM context [10]. In addition, multiple STEM-related words have a specialized meaning within various STEM disciplines (e.g., *Parent*- the simplest form of a type of mathematical function [mathematics]; organism that produces or generates another [biology]; starting component in a chemical reaction [chemistry]; first nuclide in a radioactive series [physics]) [10]. Researchers and educators in the field of STEM education have advocated the use of cooperative communication in STEM activities to foster greater semantic understandings of interdisciplinary STEM vocabulary [8], [17]. Researchers in STEM education have only recently begun to investigate the confusion resulting from the multiple meanings rife in STEM vocabulary in terms of homonyms, homophones, and homographs, and to advocate for the explicit instruction of words that fall within these categories [14], [18]. However, these categories are inadequate to fully encompass the types of words that may create barriers that hinder interdisciplinary STEM communication. Therefore, the current study incorporates conceptual categorizations found in the experimental works of cognitive and psycholinguistics.

Researchers whose work intersects the disciplines of linguistics, cognitive science, and psychology refer to words with multiple meanings as lexically or semantically ambiguous [19-22]. Within these fields, many identify and examine two primary word groups as ambiguous: homonyms and polysemes [23], [24]. Polysemes are highly relevant within the investigation of multiple meaning words because the majority of existing ambiguous words are polysemous rather than homonymous [25]. Homonyms are frequently defined within this literature as words that have two or more unrelated meanings but share a single spelling and pronunciation (e.g., *organ*- a body part; *organ*- a musical instrument) [19, 20, 22, 23]. In contrast, a polyseme is defined as a single word that has two or more closely related meanings [19-23, 26]. A polyseme can be further categorized as metonymous or metaphorical based on the relationship between its various meanings [21, 23, 27]. Metonymic polysemes are words whose meanings and their relation to one another both refer to literal referents and form some sort of recognizable relational pattern (e.g., object/content- "the *book* is heavy" & "the *book* was entertaining"; natural kind/food- "The *chickens* are laying eggs" & "We ate *chicken* for dinner"; container/contents –"She washed the *bowl*" & "She ate the *bowl* of soup") [19, 21, 23, 27, 28]. Metaphorical polysemes, on the other hand, generally refer to a word that has one historically literal meaning from which new related meanings were created through metaphorical association (e.g., *mouth* – body part; *mouth* – the point where a river enters an ocean) [21, 23, 27, 29]. There are various strategies used within linguistic, cognitive, and psychological studies that incorporate these definitions to determine whether a word is homonymous or polysemous [19, 30]. Although this distinct categorization of ambiguous words is useful for experimental design, there is general consensus among researchers in these intersecting fields that ambiguous words fall along a continuum in the degree to which their meanings differ from each other. In other words, within this continuum, homonyms' meanings share the least similarity with each other, metonymical polysemes' meanings share the most similarity, and metaphorical polysemes' meanings fall in the middle of this continuum [19]. Researchers have used this continuum as well as the more defined distinction between the terms to investigate the nuances of processing words with multiple meanings.

Although most research has focused on the comparison of polysemy and homonymy in language processing, homophones, i.e. words with the same pronunciation but two or more unrelated meanings, have also been categorized as ambiguous and therefore examined in relation to polysemy [30]. As a whole, these words are distinguished in the literature from what researchers refer to as unambiguous words, or words with a single meaning [19]. Results from previous studies indicate that words with highly overlapping meanings were easier for students to recognize and process [23, 24, 31], while words with dissimilar meanings slowed students' word recognition when compared to unambiguous words and words with similar or overlapping meanings [24]. Thus, out of the two primary types of ambiguous words, results indicate that polysemes are generally the easier type to process [24, 32, 33]. Similar results reveal that students experience less difficulty in processing polysemes than they do when attempting to process homophones, both in visual and auditory contexts [24]. However, students' performance when encountering polysemes can also vary depending on which meaning of the word is used. When encountering polysemous words during a reading task, students were able to read and understand sentences better when the meaning of the polysemous word used in the sentence best reflected the version they were most familiar with (i.e., the dominant sense of the word) rather than a less frequent or more subordinate meaning [34]. However, a student's tendency to favor one meaning of a word over another may be altered to the point that recently encountered meanings of a homonymous or polysemous word become more accessible and readily recognizable to an individual [19]. Essentially, exposure to new meanings of ambiguous words may expand students' vocabulary and ability to accurately identify the meaning of a word in a particular context. These findings link the interests of those conducting STEM language research with the prior and current research of multiple meaning words situated in a psycho/cognitive linguistic context. Therefore, the purpose of this study is to investigate interdisciplinary communication during an engineering task from a psycho/cognitive linguistic perspective.

III. Research Question

What patterns of vocabulary meaning and understanding hinder communication and progress in an interdisciplinary engineering task?

IV. Methods

The intention of this study was to examine vocabulary used by teachers while completing an engineering task. Transcriptions of responses from participants were examined qualitatively to classify any recurrent themes or discrepancies. From a linguistic perspective, ambiguous responses could be categorized as either homonyms or polysemes. Polysemes were further categorized as either metaphorical or metonymical.

A. *Participants and Setting*

Teachers attending two STEM professional development camps were participants in the study (N=40). All participants taught at the secondary level; specifically, 20 were high school teachers and 20 were middle school teachers. Disciplines of the teachers included mathematics (15), technology (3), engineering (5), social studies (3), science (10), and language arts (4). The demographics of the teachers included 2 mixed-ethnicity, 4 Asian, 6 Hispanic, 10 African Americans, and 18 White. There were 11 males and 29 females. Each of the teachers had a minimum of two years of teaching experience. Teachers were chosen as participants to examine existing discrepancies between their specialized vocabularies as any discrepancy that exists among teachers has the potential to be passed to their students. The focus of the camps was to improve communication between STEM teachers and students. Participants who completed the camps earned professional development credit. The camp took place over one week at a large, southwestern public university.

B. *Instrument*

The Aural/Spatial Interactions and Invariant Components of Vocabulary (Aural Spatial-STEM [AS-STEM]) was administered to STEM Content Area teachers to determine how content language was used before STEM professional development. Additionally, the tasks afforded evidence of developing STEM technical language. After the current researchers participated in a pilot study, they decided to adapt the instrument to observe STEM teacher conversation during various tasks. To ensure high content validity, the instrument was pilot tested with specialists and professionals of different fields, including engineering and education [8]. After examining the conversations from the teacher participants, the expectation was to provide a glimpse into the struggles students experienced when using STEM language with their peers and teachers.

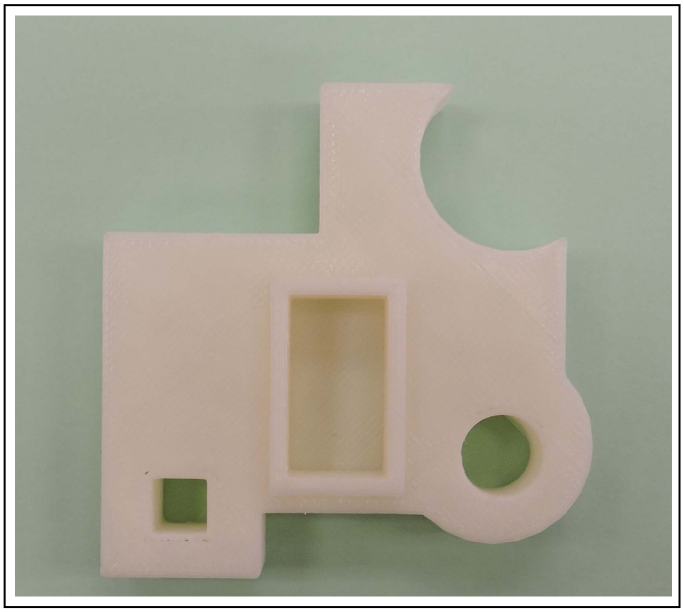

Fig. 2. Example of 3d object used in the AS-STEM instrument

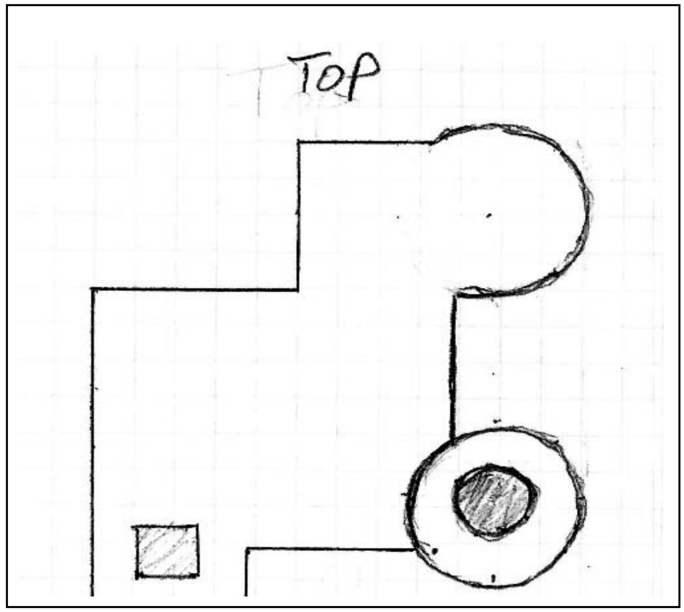

Fig. 3. Example drawing of a top orthographic view of a 3d object

During this study, the AS-STEM instrument was used to purposely assess the impact of a STEM Teacher Boot Camp on the STEM disciplinary languages that occurred during the drawing of the tasks. Participants had to verbally portray a 3-D object to other participants who were asked to draw a 2-D model (i.e., orthographic projections – See Figure 2 and Figure 3 for an example object and final top orthographic drawing) from the verbal descriptions without visual clues.

The AS-STEM tasks were run in a cognitive lab setting. Participants were divided into two groups called "drawers" and "describers". We separated them with a divider that did not allow the "drawer" to observe the model to draw. Additionally, the describer could not observe what was being drawn. Between them we placed a digital device to record their discourse. Drawers had rulers and centimeter grid paper at their disposal. Describers had a non-standard 3-D model (see example in Figure 2) and a caliper. We did not include any standard 3-D objects (cubes, dodecahedron, pyramids, or prisms). Our non-standard models were sometimes combinations of standard figures. Standard directions were delivered to each group of participants at the beginning of the cognitive lab.

Describers were given 15 minutes to collaboratively measure and verbally portray the 3-D object to the drawers. Drawers were asked to draw 2-D views. After the allotted time, drawers and describers switched roles and tools using a new unique model of roughly equal difficulty. Again 15 minutes was allotted to completing the task. Recordings of the interactions were transcribed for analysis.

C. Analysis

The data analytic strategy followed the model suggested in previous research on STEM Language [17]. First, speaking turns were determined. A speaking turn consisted of the uninterrupted dialog from one side of the partition. Once a dialog was interrupted it was determined that the turn ended and a new turn began. Turns varied in length. An example of a short turn occurred when a drawer interrupted the dialog from the describer and asking, "how many centimeters". This interruption resulted in two turns with the third turn occurring when the describer began a response to the question and continued until either the dialog came to an end or was interrupted by the drawer again. Once all the dialog was coded, the type of language was considered, how it was used, whether or not there were instances of cognitive negotiation [17] and the overall meaning of the dialog to determine if the drawer and describer were understanding each other and making progress toward the goal or cognitive negotiation. For every instance where semantic reformation was occurring the parsed articulation was examined by code looking for relationships likely responsible for the lack of progress toward the goal. Once the data were completely reduced to parsed groupings the themes emerged. Ambiguous language resulted in the greatest level of cognitive dissonance as compared to unambiguous words. Ambiguous words were categorized as either a homonym or polyseme. Polysemes were further refined as either metaphorical or metonymical. Metaphorical language was anticipated because it emerged from the data in a prior study [17] as a predominant language form once a drawer and describer realized they were not successfully communicating, the conversation transitioned to metaphors. However, in this study we are attempting to identify particular words that may support or hinder the engineering task.

V. RESULTS

There are two main categorizations of words that either necessitated clarification or led to failure on the task: ambiguous words and unambiguous words. Ambiguous words can be broken down into subcategories based on the meanings of the word in question (see Figure 1). Table 2 contains examples of these word categories within an interdisciplinary STEM context (for simplified definitions, refer back to Table 1).

TABLE II. EXAMPLES OF WORDS THAT CAN HINDER COMMUNICATION

Types of Words	**Example**	**Meaning 1**	**Meaning 2**
Homonym	Base / Bass	Foundation or lowest part	Musical Instrument
Metaphorical Polyseme	Arrow[a]	Physical object, as in archery	Symbolic representation of an archery arrow, commonly used to point
Metonymical Polyseme	Angle[a]	The point at which two or more lines meet	The indefinite space between two lines or surfaces that meet
Unambiguous Word	Catty-Corner	Diagonally opposite	None

[a] Arrow and angle are examples from the current study's data

A. *Ambiguous Words*

Words that have multiple meanings are categorized as ambiguous words and are sometimes referred to as semantically or lexically ambiguous words [35-37]. Ambiguous words can be categorized according to the relationship between the meanings associated with the word into homonyms and polysemes.

1) Homonym are two or more words that share a similar form (through pronunciation or spelling) that have two distinct and unrelated meanings [19, 20, 22, 23]. In the data, one example that caused confusion was the phrasal verb, *cut out*, as in to remove with an edged instrument, as opposed to *cut-out*, a commonly used noun in educational settings that refers to a figure formed by the cutting of paper. The object being drawn can be seen Figure 2. In the dialogue, the describer mentioned that "There's a circle cut out of our object." After thinking of an alternate way to describe what the describer was looking at, he or she said, "So now the circle that we just drew is a cut out into the [object] as if something took a big bite out of [the object]." Later, when the describer looked at the drawing and the drawer looked at the object, they realized a misunderstanding had occurred. The drawer drew the circle as if it was an indention or separate layer rather than what was intended (see Figure 3). It is possible that the drawer thought of "cut-out" the way a teacher may be used to thinking of it: like an object cut out of paper and not as the missing hole that is left behind. Knowing what the object actually looked like, the describer probably meant *cut out* in that a circle was completely cut or bitten from the object. However, this was not reflected in the final drawing. Although this particular homonym led to failure to complete the task, true homonyms, words that share meanings that are not closely related, are somewhat rare in STEM fields, in which most new words are based on existing, closely related ideas.

2) Polysemes are common ambiguous words that appear in both every day speech and technical communication. A word is a polyseme if it has two or more different but closely related meanings or senses [19-23, 26]. In linguistics research, polysemes are categorized as metaphorical polysemes or metonymical polysemes based on the relationship between the two meanings. In the current study, we identified examples of both forms of polysemes within the data.

a) Metaphorical polysemes are polysemes that have a literal meaning and an alternative, figurative meaning [21, 23, 27]. A common example in geometry and engineering design is the word face, which can mean either a part of the body or one surface of a three-dimensional object. In the current study, an example found in the dialogue was the term *arrow*, which has a physical meaning in archery, and a related, metaphorical meaning of a mark or sign. One meaning is associated with a long, slender wooden shaft attached to an arrowhead on one end and feathers or fletching near the other end. The interaction between participants in which one described a wide arrow-shaped object is given below:

> *Describer: We are going to make something like an arrow. Do you know what an arrow is? Like a bow and arrow, an arrow.*
>
> *Drawer: Yes*
>
> *Describer: Okay we are making an arrow.*

While the object being described resembled an arrow (symbol), the describer instead mentioned a bow and arrow, which brings to mind an inaccurate mental representation of the object being long and skinny. Because of this, the describer had to repeat and clarify many times throughout the remainder of the task as the drawer dealt with the conflicting representations of an arrow. In this interaction, the describer mistakenly used a metaphorical polyseme that gave the wrong idea to the drawer and slowed down progress toward completing the goal.

b) Metonymical polysemes are polysemes whose primary and secondary meanings are literal [19, 21, 23] . Because they are polysemes, these literal meanings are closely related. One common example in everyday language is chicken, which can be taken to mean the meat or the animal itself. Metonymical polysemes are much less common in STEM vocabulary than metaphorical polysemes and homonyms. However, one example that showed up in the data was the use of the word *angle*, which could refer to "the point at which two or more lines meet" (OED) or "the indefinite space between two lines or surfaces that meet" (OED). If someone were to say, "Place a point in the interior of the angle that you just drew," they would likely be referring to the latter definition. However, understanding and negotiating this meaning with clarifying language can help to resolve any problems that may occur.

B. Unambiguous Words

Unambiguous words are words that have a single definition or meaning [20, 22]. Examples include diagonally, hexagon, and stapler. Even though they only have a single meaning, unambiguous words can cause problems in communication when one person is unfamiliar with the meaning of a word being used. For example, one person may know what the term *catty-corner* means while the other person may not. This could lead to struggling to negotiate meaning, which could slow down progress on the task, or even potentially leading to failure to complete the task [38]. Within the data, the use of the term *Cartesian coordinates* halted progress on the task for one team. One person had a misconception about the meaning of this unambiguous term. The describer used this term to refer to a point described by one single number instead of the customary two. In the articulation, "Go to coordinate 6, from there draw a line down 5 boxes", the drawer indicated that he needed both coordinates. In another articulation, "Wait... wait, there should be two coordinates," the describer indicated that when given a coordinate, it was in reference to the x-axis: "I meant the x-axis." This interaction demonstrates that misunderstandings over unambiguous words can halt progress on the task. Furthermore, they had not determined a location for the origin, which provided another disconnect when attempting to plot the point. In this way, when one or both participants have incorrect meanings or no meanings associated with a word, even words considered to be unambiguous can hinder communication.

VI. Discussion

The importance of language congruity cannot be overstated. The development of the language of a discipline is essential for learning the discipline. Language, the triad of semantics, syntax, and vocabulary are interwoven and presented as being an integral component of every learning system [39]. In the earliest grades, young children learn semantics, syntax, and vocabulary in order to master each with the goal of using them to learn everything else in subsequent activities [8, 39, 40]. As students progress through school and eventually into STEM courses such as algebra, biology, mechanics, binary systems, and logistics, they encounter words they have seen before but now they will need to ascribe new meanings. When they encounter new meanings for previously defined words, they must adapt their vocabulary to encompass all of the meanings of those words.

The analysis of the data indicated that teachers used language differently and often were constrained to single definitions that were clearly situated within their own content domains. For example, "90 degrees," "extrude," "regress," and "subvert" are fully nested within only certain disciplines, whereas words like "length," "height," and "units" were commonly understood and unambiguous across the vocabularies of our participants. However, some words, such as "domain" and "range" were common to a subset. In this case, the mathematics and engineering teachers shared knowledge of these terms, whereas science, history, and language arts teachers were more likely to have to ask clarifying questions. As seen in the uses of catty-corner and Cartesian coordinates, the use of some terms that may have been previously considered unambiguous were indeed problematic.

Sometimes the drawer and describer would have a misunderstanding and it would not be noticed until later. Because this was a timed activity, they may have not realized their mistake until the end when they looked at the object and completed drawing. Two participants exemplified this situation when they noticed a problem near the end of their allotted time:

> *Describer: ...and turn back 30 degrees to meet up with the other lines. Does that make sense?*
>
> *Drawer: Um, yes. [unsure] But it's not working out. I'm getting what you're saying but I'm not getting… I think maybe you and I had a disconnect a long time ago*

Just as one mistake led to a failure to successfully complete the drawing, a single miscommunication can have major consequences in engineering tasks. Therefore, precision of language, clarifications, metaphorical language, and anything that can help to properly convey (carry) meaning are valuable in engineering and engineering education.

In this study, we learned the importance of word structures across the map provided in Figure 1. Each STEM teacher possessed a high degree of specialized vocabulary that was inadequate for communication with another teacher in a different field. At times the directions included a multiplicity of words that made unpacking the expectation nearly impossible for the drawer. Because of the ambiguity in vocabulary used, and the drawer being unable to see the object, the drawer often lacked a starting point from which to ask for clarification. These issues are not new. They are often encountered by those learning a new language but expected to also learn content in that new language. Imagine for a moment an immigrant child expected to learn mathematics in the new language. The child might have been exemplary in mathematics in the home language but when he or she encounters mathematics in the U.S. K-12 school it is situated in language, language that goes beyond his or her current comprehension of English. For these students and for students learning English in various countries and cultures, teachers should emphasize oral language and multiple meanings of vocabulary during classroom activities. There is a need for teachers to explain the correct construction of meaning surrounding STEM language and for students to speak spontaneously during class activities. Curriculum designers (e.g., problem set authors or test developers) can assist in this learning process. While developing curriculum, they must be aware of the language they use and reinforce new and potentially confusing meanings for words with many examples and problems where the new meanings can be exercised.

The focus of this study was on adult experts who were fully situated in an engineering task, albeit not a task within their respective domains of expertise. The problems that arose were linked to the lack of facility with expert language from a STEM domain that was not his or hers. These findings led to two distinct, yet fundamentally important ideas. First, if adults who have earned a post-secondary degree in a STEM subject domain experience these dramatic hindrances to performance, then students will likely suffer even more drastic learning struggles. The task was designed to be language intensive and predicated on a broad set of concepts and skills. Regardless, the structure of the task did not require more knowledge than any one teacher possessed. The complexity arose from the broad spectrum of STEM specialists involved in the attempt. The structure of the task exposed weaknesses that STEM teaching professionals possess in hopes of building a greater understanding of how language is used and taught in each STEM class. Second, the unpacking of language helps to build understanding of pitfalls in modern instruction in both preparing STEM teachers at the university level and their instruction to their students. The weaknesses exposed are linked to post-secondary instruction. If the teachers had undergone better preparation to understand the interconnections of their disciplines to other STEM disciplines, they would have been more effective with the task and would ultimately be more capable as classroom educators.

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