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How Does Students' Use of Speech Ground and Embody Their Mechanical Reasoning during Engineering Discourse?

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the NSF-funded AWAKEN Project, which documented how people learn and use engineering, and currently co-directs the National Center for Cognition and Mathematics Instruction. He is a faculty member for the Latin American School for Education, Cognitive and Neural Sciences. As part of his service to the nation, Dr. Nathan served on the National Academy of Engineering/National Research Council Committee on Integrated STEM Education, and is currently a planning committee member for the Space Studies Board of the National Academy of Sciences/National Research Council workshop Sharing the Adventure with the Student: Exploring the Intersections of NASA Space Science and Education. At the University of Wisconsin, Dr. Nathan holds affiliate appointments in the Department of Curriculum & Instruction, the Department of Psychology, and the Wisconsin Center for Education Research. He is a member of the steering committee for the Delta Program (part of the national CIRTL Network), which promotes the development of a future national STEM faculty committed to implementing and advancing effective teaching practices for diverse student audiences. Prof. Nathan currently is Director of the Center on Education and Work and Director of the Postdoctoral Training Program in Mathematical Thinking, Learning, and Instruction. He is an inductee and executive board member of the University of Wisconsin's Teaching Academy, which promotes excellence in teaching in higher education.

How Does Students' Use of Speech Ground and Embody Their Mechanical Reasoning During Engineering Discourse?

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Abstract:

This full paper concerns an exploratory study that investigates students' reasoning about torsion. Mechanical reasoning is critical to engineering applications and yet students still struggle to accurately predict, analyze, and model mechanical systems using formal symbolic notations (i.e., formalizations). To understand the nature of students' reasoning, we analyzed students' discourse to explore two competing hypotheses: (H1) The *Formalisms First* (FF) hypothesis that students report their mechanical reasoning predominantly using mathematical formalisms that take on a disembodied, allocentric (observer) point-of-view; or (H2) the *Grounded and Embodied Cognition* (GEC) hypothesis that students predominantly use independent speech which includes analogy and imagery to simulate the physical structure and function of an object(s) using an embodied, egocentric (first-person) point-of-view in addition to an allocentric point-of-view. Qualitative results from discourse analysis of two student dyads showed that students' mechanical reasoning revealed through their speech included both analogy and imagery, as predicted by H2. Students generated analogies and imagery that described dynamic behaviors, such as how torque caused displacement, stored and released energy, and fractured. Usage of analogies and imagery supports that students' mechanical reasoning often drew upon simulations of torsion-related sensorimotor experiences. Students' egocentric and allocentric imagery invoked sensorial experiences in their speech, with allocentric viewpoints being more common, as predicted by H1 and H2. Student discourse included many references to formalisms, also consistent with the H1. Data from students' verbal discourse on mechanical reasoning suggests they employ both GEC and FF viewpoints of torsion, which has implications for designing effective learning experiences and for assessing students' knowledge.

Keywords: assessment, mechanical reasoning, mechanics of materials, undergraduate engineering education

Introduction:

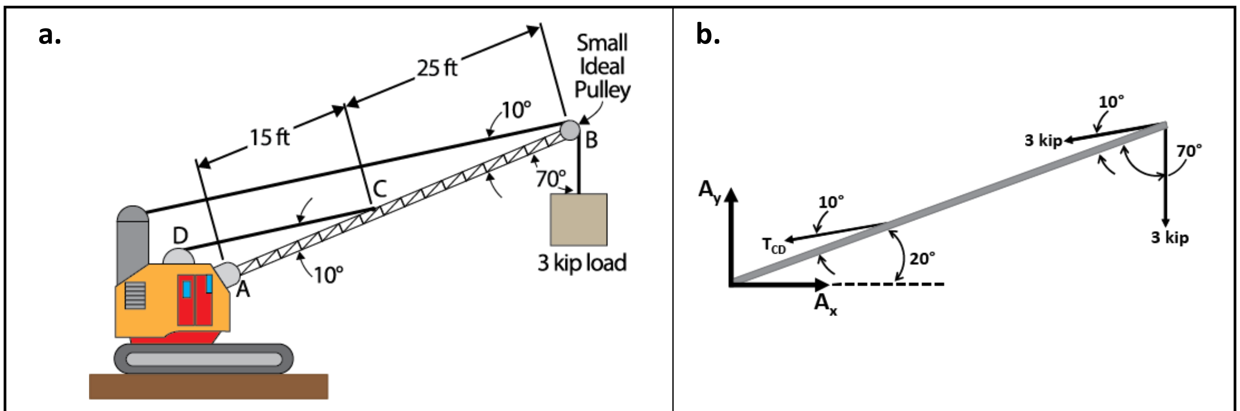
As professional engineers, the concept of torsion is crucial. Across hosts of disciplines, whether students specialize in mechanical, biomedical, civil, nuclear, or geological engineering, or engineering physics and mechanics, the concepts covered in theory-based or lab courses on torsion are foundational to understanding how physical systems behave and how to adequately design systems given torsional loads. For example, torque is experienced in transmission shafts in vehicles, structural elements in building designs, bone scaffold designs in biomechanics, and a host of other applications. However, conceptualizing torque can often be difficult resulting in numerous misconceptions when solving engineering problems.

In engineering education, knowledge acquisition traditionally stems from a *formalisms first* (FF) pedagogy that mastery of mathematical and scientific formalisms (i.e., symbolic notations of equations, diagrammatic representations, technical jargon, etc.) is required before successful application of that knowledge. In essence, the procession of learning and conceptual development requires knowledge and mastery of these formalisms before exhibiting competency in application and practice. Nathan [1] showed empirically that: (1) FF is not aligned with children's' and adults' conceptual development in STEM fields and that (2) FF encourages a formalisms-only mindset among instructors that drives out other non-formal representations (such as students' invented representations) and forms of reasoning within a problem space. Formalisms first privileges symbolic representations as a conduit for conceptualizing engineering content that does not necessarily require application or alternative ways of reasoning. In contrast, *progressive formalization* (PF) is an effective alternative because students engage in meaningful reasoning and problem solving by leveraging sensorial experiences to form a strong foundation for conceptualization before mastering symbolic representations [1].

In cognitive science, Schwartz highlights the importance of first- and second-hand knowledge [2]. In higher education, Laurillard describes these as first- and second-order experiences, attributing the differences between the two to students' difficulties learning through formalisms [3]. First-order experiences refer to people's direct, lived experiences that meaningfully apply concepts in practice, (e.g., feeling the heat after a torsional load displaces a sample). In contrast, second-order experiences are represented by formalisms in academic discourse (i.e., classroom discussions, design work, lab write-ups, and engineering case study problem-solving) that often require real-world interpretation in the absence of real-world referents. Unfortunately, these second-order experiences predominate engineering education and more broadly across STEM fields. For example, a student who doesn't touch a material (i.e., first-order) but is only shown a graph of the temperature of a material under stress (i.e., second-order) may not truly understand how torsion causes energy transfer.

Basing engineering instruction in second-order experiences limits students' abilities to develop foundational knowledge and can result in a type of gate-keeping that limit students' successes in the pre-requisites that enable their ascension of academic sequences of coursework [4]. A mechanical engineering student will typically enroll in *Statics* as a foundational course. However, the litany of second-order experiences offered instructionally in *Statics* often results in an their inability to master the concepts in preparation for the subsequent *Mechanics of Materials* course. For example, a student quantifies external forces acting on an engineering object (Figure 1.a) and uses these values to infer internal forces acting within an engineering object. Decomposed into principal components, the forces acting along the *x, y*, and *z* dimensions are formally represented using symbols, diagrams (e.g., free-body; Figure 1.b), and equations

(Figure 1.c). While these formalized ways of quantifying and equating forces offer valuable tools for modeling and analysis, they also distance students from embodying their understandings. Progressive formalization advocates that physical interactions engage our perceptions by interacting with the world. In a formalisms first approach, students may paradoxically demonstrate proficient mechanical reasoning using formalisms from second-order experiences despite still struggling to *apply* concepts in *Mechanics of Materials.* In a case study by Danielak and colleagues, they discussed how a student felt "alienated from the intellectual climate of his program" and "considered leaving engineering" after unsuccessfully rote memorizing formulae. This "alienation" emphasizes the need to discuss how engineering pedagogy disciplinary practices in ways that allow students to utilize first-order experiences not only in their epistemological sense-making, but also to instill a sense-of-belonging and inclusion in the engineering community.



c.

$$\curvearrowleft + \sum M_A = 0;\ T_{CD}(15ft)\sin 10^\circ + (3\ kip)(40\ ft)\sin 10^\circ - (3\ kip)(40\ ft)\cos 20^\circ = 0$$

$$T_{CD} = 35.3\ kip$$

$$+\uparrow \sum F_y = 0;\ A_y - T_{CD}\sin 10^\circ + (3\ kip)\sin 10^\circ - (3\ kip) = 0$$

$$A_y = 9.65\ kip$$

$$\xrightarrow{+} \sum F_x = 0;\ A_x - T_{CD}\cos 10^\circ - (3\ kip)\cos 10^\circ = 0$$

$$A_x = 37.7\ kip$$

Figure 1: Common formalized representations found in Statics textbooks in engineering education. (a.) Shows a crane with various distances, angles, and an external load. (b.) Is a simplified representation (i.e., a free-body diagram) removing potentially irrelevant information shown in (a.) as well as internal forces and angles. Distances were not added to clarify this iconic representation. (c.) Is a system of equations used to obtain solutions for the reactionary forces at point A and the tension in cable CD.

If we invoke a progressive formalization that advocates first for the usage of more grounded, first-order experiences of engineering concepts in addition to representations like free-body diagrams, we can help give students the experiential resources on which they can scaffold their understandings of second-order representations of engineering concepts. Moreover, progressive formalization allows us to develop new pedagogical tools for assessing student conceptualizations and gives us a starting point for implementing systemic change in engineering education. We argue that it is not only useful but necessary that engineering instructors and curriculum designers develop provide opportunities for learners to develop subject knowledge by benefiting from pedagogy that effectively bridges education and praxis. Ostensibly, this process is easier said than done, and behests hosts of questions—most notably is: Where do we, as members of the engineering education community, start? Is an entirely new approach needed or can we find ways to complement current pedagogical approaches to engineering curricula? As with most debates, the solution most likely is somewhere in between; this means recognizing the existing conventions effectively employed amongst experts while developing new conventions that make the foundations of engineering education easier and more accessible for novices interested in entering this profession that brings form and function to the world we live in.

Theoretical Background:

In the early 1970's, Jerome Bruner, a prominent American psychologist, disparaged the prevailing educational practice of rote memorization as a productive strategy for the acquisition of knowledge. He argued that this type of understanding did not afford the agency necessary for developing the types of robust conceptualizations that enable learners to forge their own understandings. Bruner argued against the notion that "you did not need to encounter everything in nature in order to know nature, but by understanding some deep principles you could extrapolate to the particulars as needed [5]." He further argued that first-order experiences were what informed conceptual knowledge and that cognition was undergirded by a progression from physical interactivity that provided a basic *grounding* of new ideas to formalisms. Progressing from physically *enactive* experiences to *iconic* pictorial depictions to *symbolic representations* supports, according to Bruner [6], generalization and abstraction by providing a developmental pathway from specific concrete experiences to more *idealized* and *abstract representations* that are central to STEM.

Bruner's developmental sequence, called *concreteness fading*, has substantial empirical support. At the epicenter of his work is the notion that actions—either physical and virtual—ground our understanding of complex systems and learning to represent concepts iconically and symbolically as ways for depicting and solving novel problems. Underlying the experiential affordance of concrete manipulatives is that human perception fundamentally grounds our understandings. In his seminal work, Barsalou posits that retinotopic architectures of cortical layers in the brain not only process perception, but that the cellular arrangements physically constitute what he calls "perceptual symbols" [7]. In essence, Barsalou claims that people's understandings of the physical world are organized in our brains by the perceptual experiences we garner from physical interactions through touch, sound, sight, etc.

Barsalou's work pushes against the status quo of traditional views of cognition that claimed, "cognition is computation on amodal symbols in a modular system, independent of the brain's model systems for perception, action, and introspection" (p. 617). Barsalou posited that cognition *is* modal simulations, rooted in bodily actions and perceptual experiences that are situated in one's physical environment. Essentially, Barsalou argues for *grounded cognition,* positing that perceptual symbol systems are mental states derived from our real-world perceptions that form the basis of abstractions (i.e., that first-order experiences inform second order; e.g., our experiences with chairs enable us to imagine new types of chairs, or think about the abstract category of all chairs) [8].

Complementary to Barsalou's argument that perceptual symbols *ground* cognition, another theoretical framework in the cognitive sciences is also pushing against the traditional views that human cognition, like a computer, was structured into procedural scripts that encode, store and retrieve information. *Embodied cognition* argues that all human cognition is filtered through the perceptual modalities of the body. At its burgeoning epicenter, Varela, Thompson, and Rosch, even before Barsalou, focused on Bruner's claim that cognition is *enactive* through physical manipulation of objects situated in our environment, that afferent and efferent sensorimotor subnetworks connect the mind to the body, shaping representations of the world—old and new [9]. In total, embodied cognition highlights the reciprocity between perception and conception as a prominent framework in education and the learning sciences [10, 11].

Research has demonstrated that analogical reasoning and mental imagery, as expressions of first-order experiences, are types of simulations that embody knowledge. Analogy helps establish relationships between the familiar and unfamiliar by connecting prior knowledge that is grounded in previous experiences to new concepts [12]. In learning, analogy pushes the boundaries of the unknown by re-presenting, contrasting, and generalizing. In the excerpt below from Gentner & Maravilla, the first sentence's explanation relies on formalizations (i.e., mitochondria, molecule, glucose, adenosine triphosphate (ATP), etc.) to describe cellular processes for converting fuel to molecular energy. In the second sentence, a simple analogy simplifies the functions of mitochondria by directly linking source domains to the target domains (i.e., furnace as mitochondria and heat as ATP).

> *Mitochondria take in fuel (glucose) and generate energy in the form of ATP (adenosine triphosphate, a molecule that the cell can use for energy).*
>
> *A furnace takes in fuel and generates energy in the form of heat.*

Mental imagery is often used to simulate physical and mechanical systems for making inferences about phenomena [8, 13, 14]. For example, given a static image of a gear system, people will draw inferences about the direction of rotation of individual gears by simulating the movement of each gear in sequence (see Figure 2). Typically, imagery invokes sensorial experiences that are either *egocentric* (first-person point-of-view) or *allocentric* (observer point-of-view) depending on the individual's spatial perspective [15] (sometimes referred to as spatial orientation [16]). Egocentric transformations require individuals to perceive relationships between themselves and an object while allocentric transformations require individuals to perceive relationships between objects excluding themselves within a problem space. For example, Chi & colleagues found that novice physics students often invoked egocentric speech when reasoning compared to the allocentric speech of experts [17]. In effect, novice students solved problems by creating relationships between themselves (i.e., using "I" when describing their process) and the object (i.e., formulas required to solve the problem and their relations to the problem at hand) whereas experts tended to describe the problem space from an omniscient third person perspective (i.e., using "it" when describing the process). However, this isn't to speak towards the correctness of novice and expert solutions during reasoning.

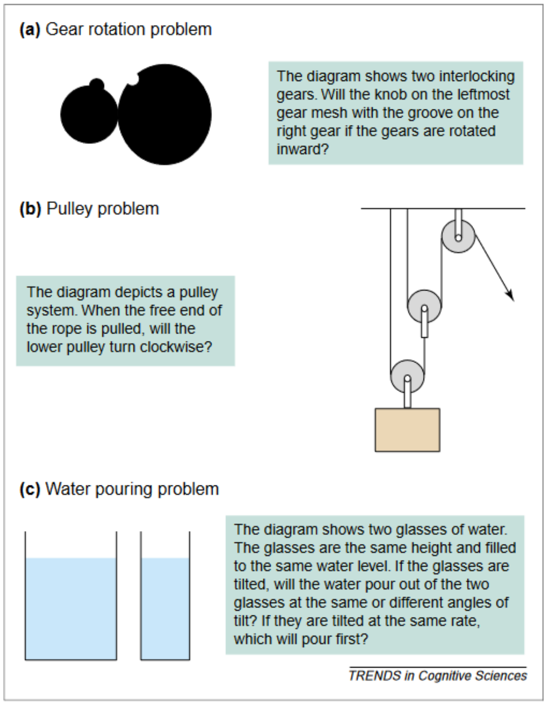


Figure 2: Examples of use of mental imagery of mechanical systems [14].

Novice engineers often invoke descriptions of physical systems dependent upon social conventions established by the engineering community, even if they may not understand them. For example, in field observations, Heath observed that the socialization of language among minoritized Black children contributed to insufficient meaning making [18]. O'Hara found that this occurs when knowledge is primarily framed within grammatical and linguistic constructions of the majority students [19]. For minoritized students in engineering education, assimilating this specific language presents obstacles in addition to reasoning about physical or mechanical systems using unfamiliar formalisms. In all, these difficulties lead us to the question: Can unconventional conceptualizations of engineering concepts contribute by establishing grounded foundations for building knowledgebase?

Knowledge assessment practices in engineering often neglect the dynamic nature of student's ability to reason about engineering concepts *independent* of formalized conventions. We hypothesize that formative assessment practices that explicitly address informal reasoning about mechanical systems may offer novel insights about students' learning by attending to students' uses of independent speech including analogy and imagery [20].

We used this framing in a *Mechanics of Materials* lab course on torsion to investigate the following research questions: (RQ1) In what ways are collaborative groups of students using formalized and independent speech—including analogy and imagery—to simulate and convey information regarding torsional loading? and (RQ2) Is there evidence of a reliance on egocentric or allocentric imagery when simulating the nature of an object under torsional loading? We hypothesize: (H1) Students' discourse will predominantly use physical and spatial analogies and imagery through independent speech that simulate the physical behaviors of an object's structure and function under torsional loading and (H2) These accounts will describe imagery both from the agent's egocentric and allocentric points-of-view.

Methods:

Participants. Male engineering students (4 students grouped into 2 dyads) who previously passed or who were concurrently enrolled a Mechanics of Materials course from various disciplines, grade levels, and coursework experiences were convenience sampled from a small summer session of a Mechanics of Materials lab to participate in the pilot study. The study took place at a predominately white Midwest university. Enrollment during the summer session for this course was eight students, four of which were either not able to attend the study or data was excluded based on no gesture or speech during reasoning. In general, the Mechanics of Materials lab offers a hands-on environment to observe and physically experience the concept of torsion, as well as the formal symbolic equations that model torsional loads.

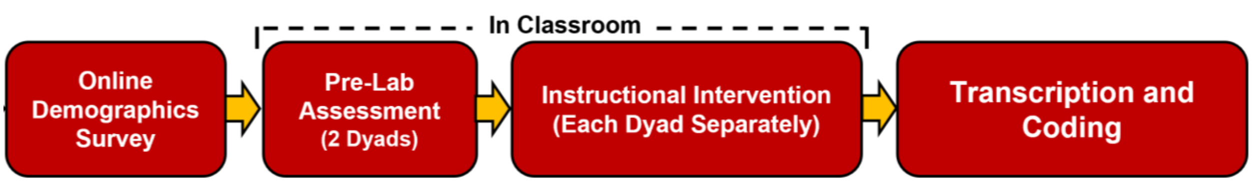


Figure 3: Schematic of experimental study design.

Procedure. As seen in Figure 3 above, students first completed an online demographics survey (Age, Ethnicity, Identified Gender, Year in School, Engineering Coursework, etc.) followed by a pre-lab assessment on torsion during which the following questions were asked:

> Prompt: You are curious to know which material will respond better under a torsional load. The samples are consistent in shape and size, only the material changes. The program for the test permits consistent angular displacements regardless of the material being tested.
>
> 1. What ways can you determine how the material responds to torsional loading? Describe any indicators in the experiment that can provide relevant information.
>
> 2. How was energy added to the specimen in the lab? How was energy released from the specimen? Describe these processes as clearly as you can.

3. Describe where the maximum shear stress occurs on the sample due to torsional loading. Why does maximum shear stress occur at this location? What information does this provide about the response of the material under torsional loading?

In answering these questions, the lab instructor prompted students to explain their responses. Following the pre-assessment, students completed a lab activity on torsional testing. Led by the lab instructor, student dyads tested samples of various metallic rods (aka, a dog-bone sample) using an ADMET material testing system (Figure 4a). Students drew a straight line (green) along the gauge length of an undeformed A36 steel specimen–a ductile material (Figure 4b); material testing concluded at failure (Figure 4c).

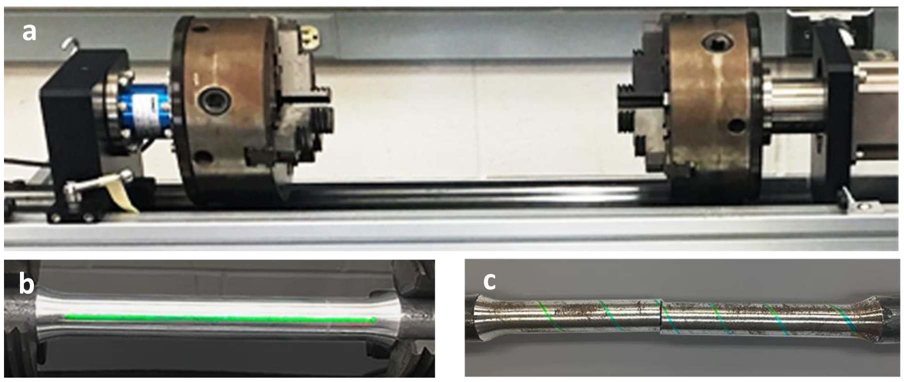


Figure 4: Equipment and testing results of torsional loading. (a) Displays the ADMET material testing system. (b) shows an undeformed sample; the green line provides students with a visual representation prior to deformation. (c) an image of a deformed sample with the green line providing students a visual representation of deformation at fracture.

Data Collection. Participants' pre-test interviews and torsional testing activities were video recorded and transcribed. Transcript analysis focused on knowledge construction, idea creation, joint understanding, and collaborative problem-solving in institutional and cultural contexts aligned with embodied theories of cognition using sociocultural discourse analysis (SCDA) [21]. Through SCDA, students' collaborative speech was analyzed for instances of formalized and independent speech which includes analogy, and imagery. Table 1 provides the coding schema and definitions.

Table 1: Coding schema of verbal reasoning used to describe conceptualizations of torsional loading.

Code	Definitions
Formalized Function	Used to describe the **function** (i.e., dynamic or time-dependent) nature of an engineering object within the problem space. Participant generates this description **within** the bounds of theory-based terminology in Mechanics of Materials.
Formalized Structure	Used to describe the **structural** (i.e., static or non-temporal) nature of an engineering object within the problem space. Participant generates this description **within** the bounds of theory-based terminology in Mechanics of Materials.

Independent Function	Used to describe the **function** (i.e., dynamic or time-dependent) nature of an engineering object within the problem space. Participant generates this description **outside** of theory-based terminology in Mechanics of Materials.
Independent Structure	Used to describe the **static** (i.e., non-dynamic or non-temporal) nature of an engineering object within the problem space. Participant generates this description **outside** of theory-based terminology in Mechanics of Materials.
Functional Analogy	Used to **compare** between the problem space's **target domain** and a non-problem space's **source domain**. Comparisons between target and source domain focus on **function** (i.e., dynamic or time-dependent) of an engineering object.
Structural Analogy	Used to **compare** between the problem space's **target domain** and a non-problem space's **source domain**. Comparisons between target and source domain focus on **structure** (i.e., static or non-temporal) of an engineering object.
Allocentric Imagery	**Invoking sensory experiences** within the problem space in which the participant is placing **others** at or around the center of the problem space.
Egocentric Imagery	**Invoking sensory experiences** within the problem space in which the participant is placing **themselves** at or around the center of the problem space.

Results:

The first research question (RQ1) investigated the ways collaborative groups of students were using analogy and imagery in independent speech to simulate and convey information regarding torsional loading; specifically, how their verbal reasoning expressed these processes. We hypothesized (H1) that students' discourse would predominantly use physical and spatial analogies as well as imagery to simulate the structural and functional physical behaviors of an engineering object under torsional loading. Analysis of students verbal reasoning from the pre-lab assessment (including their discussions with the lab instructor) indicated that students predominately relied upon formalized speech when describing the structure and function of engineering objects under torsional loading. Table 2 provides frequencies for students formalized, independent, analogical, and imaginative speech. In general, students' explanations included the formalized speech taught in the theoretical (i.e., not lab) Mechanics of Materials course, with some instances of students drawing upon other personal experiences or other coursework to explain engineering concepts that included instances of analogy and imagery. Below are several examples of how the coding schema was applied for each of the pre-assessment questions and transcripts of participants demonstrating instances when students' usage of formalisms were incorrect.

Table 2: Coding Scheme for verbal descriptions of torsional loading conceptualization.

Code	**Frequency (Count)**
Formalized Function	70
Formalized Structure	48
Independent Function	51
Independent Structure	57

Functional Analogy	8
Structural Analogy	13
Egocentric Imagery	2
Allocentric Imagery	25

Q1: You are curious to know which material will respond better under a torsional load. The samples are consistent in shape and size, only the material changes. The program for the test permits consistent angular displacements regardless of the material being tested. What ways can you determine how the material responds to torsional loading? Describe any indicators in the experiment that can provide relevant information.

P1: *We were kind of just identifying the mechanical properties [Formalized Structure], the cross-sectional shape [Formalized Structure], Young's modulus G [Formalized Structure], and the temperature thermal component too [Formalized Structure].*

P2: *If it's hardened [Independent Function] or annealed [Independent Function] or the grain structure of the metal [Independent Function], if you really want to get into it, I guess.*

P3: *The first thing that comes to mind is whether or not material is brittle [Formalized Structure], depending on whether it… ...if it is a brittle material [Formalized Structure] than it will fracture [Formalized Function]… ...and there, there'll be a very like parallel [Independent Structure] fracture point [Formalized Structure]. Whereas like a more ductile material [Formalized Structure] sort of bends [Formalized Function].*

P4: *It's loaded [Formalized Function] by like a, like by uh… ...a clamp [Independent Structure] like a twisting [Independent Function], a clamp [Independent Structure] twisting [Independent Function].*

Q2: How was energy added to the specimen in the lab? How was energy released from the specimen? Describe these processes as clearly as you can.

P1: *I have uh… energy [Formalized Function] goes into the bonds [Independent Function] as it and then is released [Independent Function] when it releases [Independent Function] unless it's into the plastic [Formalized Function] portion, then that energy [Formalized Function] goes into breaking [Independent Function] those bonds [Independent Function] and the excess energy [Formalized Function] goes into friction [Formalized Function] like heat [Functional Analogy], noise [Functional Analogy], etc.*

P2: *Well, if the material's in its elastic state [Formalized Structure], then if you twist it [Independent Function, Allocentric Imagery], and then you release it [Independent Function, Allocentric Imagery], it's going twist back really fast [Independent Function, Allocentric Imagery]. That's a release [Independent Function] of energy [Formalized Function] right there [Allocentric Imagery].*

P3: *I guess we can also add that like the example of say twisting a rubber band [Functional Analogy]. You can see that the the material [Independent Structure] of a rubber band [Allocentric Imagery] is twisted up [Functional Analogy]. It's where you'd really see, you can tell that it returned [Independent Function] to its original position [Independent Structure, Allocentric Imagery].*

P4: *Energy [Formalized Function] can be released [Independent Function] by untwisting [Independent Function] it back to its normal position [Independent Structure] or by twisting*

[Independent Function] it so much that it breaks [Independent Function]. So, energy [Formalized Function] could be released [Independent Function] due to a fracture [Formalized Function] or by… ...releasing the torque [Formalized Function] and returning the material [Independent Function] back to its normal position [Independent Structure], initial position [Independent Structure].

Q3: Describe where the maximum shear stress occurs on the sample due to torsional loading. Why does maximum shear stress occur at this location? What information does this provide about the response of the material under torsional loading?

P1: *Because the arc length [Formalized Structure] is. Yea, the further out you go whatever rotates [Allocentric Imagery] that arc length [Independent Structure] gets bigger and bigger [Independent Function] for the same theta [Formalized Structure].*

P2: *Because it's the greatest radius [Formalized Structure]. And it also does actually make sense because when you think about it like, imagine you were like [Egocentric Imagery], we're ro.. [Allocentric Imagery, Egocentric Imagery] we're rotating [Independent Function, Egocentric Imagery, Allocentric Imagery], the molecules wouldn't move [Independent Function] relative to each other way more on the outside [Independent Structure] than inside [Independent Structure], because it's the neutral axis [Formalized Structure]. So it does make sense that shear force [Formalized Function] would be a lot greater [Independent Function] on the outside [Independent Structure] than the inside [Independent Structure].*

P3: *So the maximum shear stress [Formalized Function] would occur at the outermost radius [Formalized Structure] of the given… ...specimen [Formalized Structure] or just material [Independent Structure], because it is where it has the most displacement [Formalized Function]. And that's just due to the fact that because the rotation [Independent Function] acts around the axis [Formalized Structure] or central-most point [Independent Structure] of the material [Independent Structure], the radius [Formalized Structure] is greatest on the exterior [Independent Structure] and so it's be… ...it is moving the most during that [Independent Function].*

P4: *The maximum shear [Formalized Function] occurs on the outer radius [Formalized Structure]... It's farthest away [Independent Function] from its like center [Independent Structure] of...*

In the excerpts above, even though students used formalized speech most frequently, they used formalized statements of function and structure incorrectly to describe answers more often than when they used other forms of speech. For example, in the first dyad, P1 incorrectly applied a formalism to represent the thermal expansion coefficient "α" (alpha) and P2 described how the material displaces by bending under torsional loading resulting in energy addition. In the second dyad, P3 incorrectly reasoned about failure modes between brittle and ductile materials and P4 incorrectly reasoned the type of stress developed during torsional loading. This demonstrates a disconnect between formalized ways of knowing and correct conceptualizations that arise when students do not leverage more grounded ways of knowing that can improve explanations. Below are additional examples of students' incorrect verbal reasoning using formalisms.

P1: *Alpha [Formalized Structure] is **thermal component** [Formalized Function], right?*

Above, P1 conflated formalisms taught in the Mechanics of Materials course. Although alpha can represent the thermal expansion coefficient, in the context of answering the pre-lab assessment questions, alpha also represents the angular acceleration of the material undergoing deformation.

> P2: *When you **bend** metal [Formalized Function, Allocentric Imagery], it also heats it up [Independent Function] so that's another way that energy's added [Formalized Function].*

From the content of the lecture focusing on torsion, P2 mentioned bending of the material which develops a different type of stress—bending stress—compared to torsional shear stress. In the follow-up discussion with the lab instructor, the student again referred to this bending of the material to conceptualize how energy is added. Although true, in the case of forces creating a bending moment, this is an incorrect conceptualization for an engineering object undergoing a torsional load.

> P3: *The first thing that comes to mind is whether or not material is brittle [Formalized Structure], depending on whether it… ...if it is a **brittle material** [Formalized Structure] than it will fracture [Formalized Function]… ...and there, there'll be a very like **parallel** [Independent Structure] **fracture** [Formalized Structure] point. Whereas like a more **ductile material** [Formalized Structure] sort of **bends** [Formalized Function].*

Here, P3 reasoned about how different materials—brittle and ductile—fracture and how these fracture modes provide indications of a material response to torsional loading. The student incorrectly reasoned that a brittle material will fracture in a parallel-like manner. The term "parallel" is not normally mentioned in the theoretical Mechanics of Materials course and was a term independently created by the student to describe the nature of the brittle fracture, although parallel is a sufficient description of a ductile fracture. Further, the student incorrectly used the term "bends" when describing the result of a material undergoing torsional loading.

> P4: *You can also respond to the material [Independent Structure], you can see how the material [Independent Structure] responds depending on the material [Independent Structure] you can physically see.... …is that a **transverse shear** [Formalized Function]?*

In this case, P4 reasoned about how a material responds under torsional loading. The student incorrectly reasoned that a sample undergoing torsion will experience a transverse shear instead of torsional shear stress.

The second research question (RQ2) investigated students' reliance on egocentric or allocentric imagery when simulating engineering objects under torsional loading. We hypothesized (H2) that students' imagery would take both egocentric and allocentric point-of-views. Analyses indicated that students predominately used allocentric imagery when reasoning about an engineering object undergoing torsional loading. Table 3 below provides the frequencies for imagery with formalized and independent speech, as well as analogical reasoning. In general, students relied more on allocentric imagery to describe the structure and function when they provided explanations independent of Mechanics of Materials formalisms. Below are some additional examples of students' usages of imagery.

Table 3: Egocentric and allocentric matched to other modes of verbal reasoning.

Coding Schema	Egocentric Imagery	Allocentric Imagery
Formalized Function	0	8
Formalized Structure	0	9
Independent Function	1	13
Independent Structure	0	13
Functional Analogy	0	1
Structural Analogy	0	1

> P2: *And it also does actually make sense because when you think about it like,* ***imagine you were like [Egocentric Imagery], we're [Allocentric Imagery, Egocentric Imagery] ro... …we're rotating [Independent Function, Egocentric Imagery, Allocentric Imagery]****, the molecules wouldn't move [Independent Function] relative to each other way more on the outside [Independent Structure] than inside [Independent Structure], because it's the neutral axis [Formalized Structure].*

In response to the third pre-lab question regarding the location of maximum shear stress, P2 from the first dyad used ego- and allocentric imagery and independent functional speech to reason about the movement of molecules in a sample undergoing torsion. Their imagery placed themselves and or their partner at the center of problem space and described being rotated.

> P2: *But yeah, you know a little we did this in uh mechanics of materials, but with a cross-section [Formalized Structure], and* ***you draw a bigger, bigger arrow [Allocentric Imagery, Independent Function]*** *further outside [Independent Structure] you get because you know, bigger shear stress [Formalized Function].*

The same student (P2) used imagery to describe the distribution of shear stresses from the neutral axis of the material to the outer edge of the sample. In this example, P2 used independent functional speech to describe the second-order depiction (e.g., drawing a bigger arrow) of how stress distributions shift from the neutral axis.

> P1: ***Greater layer displacement [Formalized Function], the further out you go [Allocentric Imagery],*** *the greater the circumference [Formalized Structure] and the more it shifts from its original position [Independent Function].*

In the same dyad, P1 described how individual boundary layers within a materials cross-section displaced as the layers shifted from the neutral axis to the outermost boundary layer of the engineering object. They invoked allocentric imagery by placing their partner at the center of the problem space (i.e., the center of the sample being tested).

Discussion:

Engineering students' knowledge is often assessed based on performance of formalized, written tasks. The findings of this exploratory study suggest that a much of students' developing mechanical knowledge is evidenced through embodied representations such as speech. These include simulated actions that are grounded in perceptual experiences that offer richly independent ways of conceptualizing engineering phenomena, including mechanical and spatial analogies, as well as ego-and allocentric imagery. Evidence of embodied understandings is present in students' speech that also offers educators additional opportunities to evaluate student learning beyond the bounds of traditionally formal, written assessments. The current study supports that these embodied forms of reasoning can serve as solid foundations for expanding knowledge of materials and systems and ground the meanings of theoretical constructs and formal equations that represent structures and functions in engineering.

This exploratory study investigated verbal reasoning used by engineering students' developing knowledge of torsion (RQ1) and the reliance on ego- and allocentric imagery when simulating the nature of an engineering object under torsion (RQ2). Transcription analysis of video-recorded pre-lab assessments and discussions with the lab instructor showed that students were verbally reasoning with their classmates and lab instructor through different modes (i.e., formalized speech and independent speech including analogy and imagery) (as shown in Table 2). In this discussion, we look to broaden the perspective by offering anecdotal accounts of learning along with practical implications for improving engineering education.

Formalized symbolic representations of quantitative relations, as noted by Koedinger & Nathan, can be difficult to understand and consequential during problem-solving [22]. Although their work focused on algebra, they concluded that formalized representations affected performances and learning, mitigated by how easy a representation was to comprehend (i.e., difficulty), or whether or not the representation was reliably meaningful to strategizing about solutions. Reasoning that is independent of these formalisms allows students to apply their lived experiences directly in developing concrete understandings of engineering phenomena. In the current study, participants provided more conceptually correct answers independently compared to the use of formalized speech when reasoning about torsion. This suggests that their ways of reasoning, which included analogy and imagery, eased their ability to comprehend salient features when answering the pre-lab assessment questions and in their discussions with the lab instructor.

Since engineering education draws from many other disciplines, including physics and mathematics, there is often a crossover between the symbols that represent different quantifiable entities. Given that there are limited numbers of symbolic representations across fields, confusions can arise when formalized syntax carries differences in meaning [23]. In our results, we saw how a student's reasoning about torsion confused the representation "α" (alpha) to be the thermal expansion coefficient instead of angular acceleration. Thus, many students who might be attempting to apply formalized knowledge about concepts from different courses can become confused while trying to make sense of new concepts. In other examples, we saw students confusing bending stresses with torsional shear stresses; at the crux of these types of stresses is how they develop through a force acting at a distance. Of course, it may be the case that students have yet to hone the spatial abilities [24-26] necessary to adequately envision how these stresses develop in three-dimensional space, flipping between different planes when reasoning about potential solutions. However, it seems incumbent on engineering educators to clarify differences between these two types of stresses symbolically, given the crossover between symbolic representations that may cause confusion and result in misconceptions. In these case studies, as well as our previous work [27], we see the clear need to consider how students are verbally reasoning as a means for identifying their misconceptions.

Although this study reports identifiable patterns in discourse that emerge in students' verbalizations as they reason about mechanical systems in an engineering lab course, there are some limitations we must address. First, as a case study with two participating dyads, we are limited to a qualitative assessment that leaves us unable to generalize these findings statistically. Instead, we present a well-evidenced theoretical justification for why we hypothesize that these trends in the data would continue across a larger sample. We are currently processing the data from an *in-situ* intervention with 15 sections (189 students) of an engineering lab on torsion. Not only will this dataset have the needed statistical power for quantitative analysis, but we will also be able to identify embodied pedagogical components that contribute to successful conceptualizations and applications of knowledge. Further, the larger data set more closely aligns with the broader population of students regarding demographics. Thus, the current study is meant to guide engineering educational researchers to future research with hopes of reaching engineering educators and their classrooms.

Assessing learning requires considerations of more than just students’ verbalized reasoning through formalisms. There may be interactions between multiple modes of simulation used when reasoning that could provide evidence for improving learning outcomes for engineering students. Thus, we advocate for a progressive formalization that integrates grounded embodied learning through experiences, and the inclusion of gestures as well as other forms of non-verbal expressions, because they enable researchers to document the ways that learners simulate physical and mechanical systems. In combination, speech and gestures result in a stronger, grounded foundation for knowledge building, thereby increasing ease of comprehension of higher order concepts and performances in later coursework [28]. Future studies that investigate verbal utterances including analogy and imagery as well as nonverbal forms of knowledge expression, such as gestures, will greatly expand the tools with which researchers and educators can assess students’ emerging mechanical reasoning.

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