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EMPIRICAL RESEARCH

Students' Approaches to Studying through a Situative Lens

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Background: Over the last 50 years, education researchers have sought to relate students' *approaches to learning* with the depth of understanding that results, leading to the characterization of individual students as deep learners or surface learners. Treating approaches as an individual characteristic places blame on students labeled as surface learners and leads to missed opportunities by instructors to change the way those students orient towards learning.
Purpose: Alternatively, we characterize students' tacit operations that may be oriented towards rote learning or conceptual learning in terms of the collective activity of learning in school as produced by an object-oriented, tool-mediated activity system.
Design/Method: Using a thematic analysis, we investigated the situated written self-reflections of 180 junior-level engineering students. We identified themes and categories of the experiences in the activity system they described that influence their rote and conceptual learning operations.
Results: The types of assignments and assessments students complete are the most frequent element cited in prompting them to activate either rote or conceptual learning operations, and must be considered in conjunction with student-centered classroom practices in order for the latter to be effective at encouraging conceptual operations. Elements of the educational system, including the importance of grades and time constraints, formed a more interconnected network than those in the conceptual learning network and encouraged rote learning operations. While these responses were less numerous, students used strong language associated with despair and inevitability.
Conclusions: Instructors and administrators should consider holistically their program's activity system in order to encourage students' adoption of conceptual learning operations rather than focusing on changing isolated elements of the system.

Keywords: activity theory; chemical engineering; conceptual learning; mixed methods

Introduction

There is a rich literature relating students' learning outcomes to how they approach learning (Bunce et al., 2017; Case & Marshall, 2004; De Clercq et al., 2013; Ellis & Bliuc, 2019; Entwistle & Ramsden, 1983; Marton & Säljö, 1976; Trigwell & Prosser, 1991; Tudor, 2013). Taking a cognitive perspective, most studies presume that the approach is an inherent characteristic of the individual learner. This perspective has led to the binary notion that students act as either *deep learners* who develop a meaningful understanding or *surface learners* solely doing what is required to reproduce answers and get a grade (Marton & Säljö, 1976). Deep learning has been associated with higher levels of self-regulation and intrinsic motivation, while surface learning is associated with poor self-regulation and extrinsic motivation (Entwistle & Ramsden, 1983; Fransson, 1977; Ramsden, 1992).

Such a view, however, can place blame on learners' individual characteristics for prompting their adopted approaches. This perspective downplays the role of the educational system and cultural environment in which students are performing this learning. For this reason, we shift to a situative perspective where we seek to understand the variation in students' learning operations through the activity system, the interconnected network of rules and tools which students use to complete their objective of *doing school* (Greeno, 1998). Through this lens, the classroom setting and its social rules—those behaviors, values, and actions that have become ingrained in both the students and, importantly, their instructors—are central in considering how students adopt learning operations and in developing strategies for change.

There have also been studies that provide evidence that some individual students will shift their approach from surface learning to deep learning depending on instructional characteristics of a class. In general, *student-centered* classes focusing on active learning and sense-making demonstrate a greater proportion of students with deep learning approaches than *teacher-centered* classes that focus on knowledge transmission (Kember, 1997). Proponents have appropriately interpreted these studies to recommend that instructors shift to student-centered pedagogies. However, this response does not address the finding that even in these student-centered classes, often most students report surface approaches (Eley, 1992), again suggesting an investigation of the activity system in which students *do school* is warranted.

Our goal for this study is to use the activity system framework to articulate a more holistic approach in addressing how students engage in their learning and then to identify the ways such a perspective can provide faculty and administrators guidance to take action. To achieve this goal, we ask a cohort of third-year engineering students to describe the ways in which they are prompted to approach studying. To explore and explicate students' learning operations through a situative lens, we shift our methodology from survey instruments designed to measure students' approaches to learning to a situated written self-reflection assignment where students read a paper about studying approaches and then relate them to their current schooling experiences. We use these reflections to characterize the elements of the activity system (the collective activity in a set of required junior-level courses) that students identify as promoting the adoption of either a strategy which focuses on understanding course concepts, or a strategy emphasizing memorization and reproduction of content and then illustrate those elements with examples from student writing.

We ask the following research questions:

1) In the context of a student-centered class, what elements of the learning environment do students perceive that influence their adoption of rote learning operations? Of conceptual learning operations? Which elements appear most frequently?
2) How do the identified elements that prompt either rote or conceptual learning operations connect together? Which elements are associated with the strongest emotional affect?

Approaches to Learning

In this section, we briefly review the literature on student approaches to learning. While this construct has been valuable in helping educators understand individual differences in students, and to respond to them, we argue that these studies consider the approach to learning as a characteristic that resides in the learner rather than being the product of the activity system in which that student does school.

Approaches to learning trace back to Marton and Säljö's (1976) classic study of how students approached a reading assignment. Marton and Säljö identified two distinct groups of students—one focused on developing their own understanding and another focused on reproducing content. The former group's approach was termed *deep,* and the latter group's was termed *surface.* Later work identified a third approach, called *strategic* (Entwistle & Ramsden, 1983) or *achieving* (Biggs, 1987). Strategic learners consider what is required in order to receive high grades, and adopt the relevant approach. However, some researchers have argued the strategic approach is simply a facet of the deep approach (Kember & Leung, 1998; Zeegers, 2004).

A deep approach to learning is characterized by a student's focus on meaning and concepts, formation of connections between current and previous courses, and the relation of content to previous knowledge and real life (Biggs, 2003). Conversely, when adopting a surface approach, students do not seek to form connections between concepts or previous content, instead seeing the knowledge as separate pieces. They tend to learn the material in an ad hoc manner as needed for an exam or assessment (Biggs, 2003). The deep approach often correlates with better learning outcomes, such as ability to explain the material, as well as higher course grades (Asikainen et al., 2013; Entwistle & Ramsden, 1983; Bunce et al., 2017; Trigwell & Prosser, 1991).

Two families of survey instruments are commonly used in order to measure students' perceived approaches to learning, one set evolving from the Approaches to Study Inventory (ASI) (Entwistle & Ramsden, 1983; Entwistle & Tait, 1994; Tait et al., 1998) and another from the Study Process Questionnaire (SPQ) (Biggs, 1987; Biggs, Kember, & Leung, 2001; Zeegers, 2002). These instruments have been used to investigate whether changes in pedagogy have resulted in changes to students' approaches to learning (Cifuentes, Xochihua, & Edwards, 2011; Hamm & Robertson, 2010; Offir, Lev, & Bezalel, 2008; Phillips & Graeff, 2014), to target students in need of assistance (Brown, Wakeling, Naiker, & White, 2014), and to investigate the relation between students' approaches to learning with technology (e.g., online learning) and their learning outcomes (Ellis & Bliuc, 2019). Larger, university-wide studies have used student approaches to learning instruments alone, or in conjunction with other survey instruments (e.g., the Course Experience Questionnaire, Ramsden, 1991), in order to study student perceptions of their learning environment in relation to their adopted approaches to learning (Lizzio, Wilson, & Simons, 2002) or to compare students' approaches at different universities (Biggs & Kirby, 1983).

These studies suggest that a variety of factors promote the adoption of surface or deep learning approaches. Assessments play a key role with students choosing the approach that will be rewarded on exams or homework (Biggs, 1987; Entwistle, 2000; Entwistle & Ramsden, 1983). Students also recognize the role of their instructors' pedagogical choices. Teacher-centered classrooms (Prosser, Trigwell, & Taylor, 1994), where transmission of information was the focus, were found to promote surface learning, while student-centered classrooms, where student understanding was the focus, were found to promote deep learning. An appropriate workload has also been found to enable a deep approach, while students who felt overwhelmed tended to adopt a surface approach (Lizzio et al., 2002). These studies typically treat these contextual factors (assessment, pedagogy) as isolated independent variables rather than as connected elements in an activity system.

However, there are studies that suggest a focus on activity systems is appropriate. Reported learning approaches are not intrinsic to a student (Entwistle & Ramsden, 1983). Students adapt their approach based on the context of their learning environment, and have been shown to shift their approach over time in a given course (Case & Marshall, 2004; Marshall, Summer, & Woolnough, 1999). Learning approaches have also been linked to students' motivations, whether they are intrinsic, with a desire or interest to learn the material leading to a deep approach, or extrinsic, with a lack of interest or pursuit of grades leading to a surface approach (Fransson, 1977; Ramsden, 1992). However, such motivations are not immutable but rather influenced by elements of the learning environment. To consider the students' individual motivations without regard to their learning environment's influence misses much of what promotes their choices of how and what to study.

Theoretical Framework

In this study, we take a situative perspective of learning which conceives of the learner's behavior and agency as inseparable from the social context in which the learner resides (Engeström, 2001; Greeno, 2006; Johri, Olds, & O'Connor, 2014; Vygotsky, 1978). In this sense, the learner cannot be considered in isolation, but must be understood to be taking part in coordinated systems that include social processes (e.g., the interactions between student and instructor) complete with their own set of rules (e.g., classroom expectations, values, and behaviors). The interplay between these social processes, while extremely complex, is recognized and adopted by the students. Learning, therefore, is an encultured process, and students develop their own understanding of learning as they grow and move through various learning environments, each with their own rules (Brown, Collins, & Duguid, 1989). Different arrangements of activity, then, lead to different forms of learning (Greeno, 1998). What kinds of questions are valued, which language to use, and what behaviors are appropriate are all parts of the rules of activity in which the students do school. From the situative perspective, the practices by which students learn are, in themselves, a key aspect of what they learn.

Therefore, we must understand the students' actions as the result of systematic tensions in their environments and their encultured responses (Engeström, 2001). To do so, we consider the collective activity of learning in school in terms of an object-oriented, tool-mediated activity system (Engeström, 2001; Vygotsky, 1978). Following Vygotsky (1978), **Figure 1a** shows the elements of the first-generation activity system that we focus on in this study, consisting of subjects, objects, and mediational tools (Engestrom, 1999). The subject is the people engaged in activity (students, instructors, advisors). The object (learning, grades) motivates the activity of the subject and directs a set of action. In fact, underlying the object are the needs and desires to which the activity responds. In addition, the object is not immutable but can change as a result of activity (Nardi, 1996). The tools are both material (such as a textbook or homework assignment) and semiotic (language and framing an instructor uses) (Wertsch, 1991, 1994). Importantly, the activity system extends beyond considering contextual factors as separate from the individual (and which act on the individual), but rather it views subject, object, and tools as mutually constituted and constantly transforming one another (Barab, Evans, & Baek, 2004). Neither the tools nor the subjects can be studied in isolation, as the context in which the tools are being used influences how they are adopted or understood by the individuals being acted upon. In summary, to understand student learning, we advocate for *not* just considering the learning environment and culture of schooling as a context to be managed and explained as contributing to learning. Rather, this analysis treats subjects engaged in activity that moves toward an object as inextricably intertwined with the tools that mediate the activity.

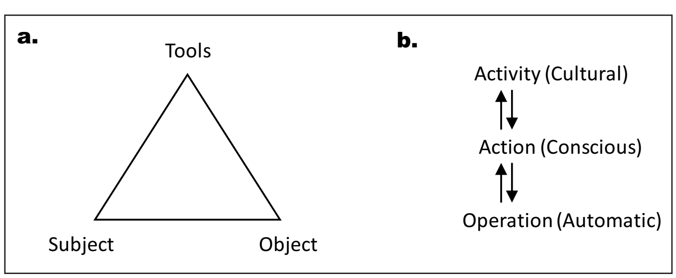

Figure 1: (a) Elements of the activity system **(b)** hierarchical levels in activity.

Figure 1b shows the hierarchical relationship between levels of activity, action, and operation within the activity system (Barab, Evans, & Baek, 2004; Leont'ev, 1974). Activity (doing school) consists of the performance of a series of actions (doing homework, studying for exams) that are undertaken in service towards producing the object. Actions are carried out through operations. Importantly, operations are routinized and implicit. Nardi (1996) provides an example of an operation as an experienced driver shifting gears of a car with manual transmission. As the double arrows in **Figure 1b** indicate, levels are not fixed but can move both up and down. For example, when first learning to drive, shifting can be considered an action which requires conscious effort, but with time it becomes an operation. Correspondingly, during a student's experience in school, rote learning actions (memorizing for spelling quizzes, for multiplication tables, etc.) become routinized and encultured, which leads them to become unconscious rote learning operations. Conversely, when changes in elements of the activity system prompt it, the reverse can occur and routinized operations can revert to conscious actions (Leont'ev, 1974). In summary, of the three hierarchical levels depicted in **Figure 1b**, individuals are general only aware of their conscious actions which are supported by routinized operations and conditioned by cultural activity (Barab et al., 2004).

Using activity systems, we reframe consideration of students' approaches to learning. The constructs of deep learning and surface learning are multi-faceted and contain several aspects (e.g., action, regulation, motivation). We shift to constructs of *rote* and *conceptual* learning, which we define as routinized operations that students perform while undertaking actions in the activity of doing school. A rote learning operation is characterized by a literal and inflexible assimilation of new knowledge in action, such as memorizing (Ausubel, 1963). In this manner, rote learning makes it difficult for students to notice associations to other knowledge. In a conceptual learning operation, new ideas are related to previous understanding, which, in turn, develops and expands. Leach and Scott (2003) elaborate that the conceptual learning operation is characterized by students making "sense of the talk that surrounds them, relating that talk to their existing ideas and ways of thinking. Learners must reorganize and reconstruct the talk and activities of the social plane" (p. 101–102). This type of learning naturally leads to characteristics shown by experts where concepts are interconnected, and can grow and change with activity (Bransford, Brown, & Cocking, 1999).

We are interested in how the activity system of a cohort of junior-level engineering students influences their operations of rote and conceptual learning. Elements of the system include the nature of the tools they use, the social norms among the subjects, and the object of their activity. We seek to understand activity as a dynamic phenomenon that is historically rooted and can change over time. Using activity theory then, we might ask what conditions are necessary to shift the operation of rote learning into an action that can be changed and directed towards conceptual learning?

Methodology

In this study, we are interested in characterizing students' experiences of the ways that their cohort-level activity system prompts their learning operations. As the primary data source, we use written responses from a contextualized exercise which was designed for students to reflect on their study practices. While individuals are generally only aware of their conscious actions (Barab et al., 2004), the students' descriptions reveal ways that those actions are supported by routinized learning operations and are conditioned by the cultural activity of doing school. Thus, the study design enables us to explore and interpret the interactions between the hierarchical levels of operations, actions, and activity.

We seek to investigate how a cohort of students experience the activity system of doing school. We are not interested in characterizing how students engage in the rote or conceptual learning operations themselves, but instead in how students experience their environment as prompting them to adopt these operations. We use a thematic analysis which draws on elements of phenomenography (Marton, 1981) as developed by Prosser and colleagues (Crawford, Gordon, Nicholas, & Prosser, 1994; Prosser, 1994; Prosser, Walker, & Millar, 1996). A key aspect of phenomenographic research is that a single learner's experience of their activity system can be different from that of another learner, even though they both participate in the same learning environment. This variation results in a distribution of experiences and perspectives which in turn, describe the phenomenon being studied (Marton & Booth, 1997). The qualitative categorization of a cohort's perspectives of their learning environment allows us to determine key aspects which prompt rote and conceptual operations, as well as their frequency and the associated affect.

While data sources in phenomenographic studies are typically oral interviews, we follow Prosser and use written responses to open-ended questions. Written responses allow for more expedient analysis, and therefore larger sample sizes, enabling us to collect data from an entire cohort without sampling biases. The larger sample sizes also afford quantitative analysis of the proportions of participants who identify a given aspect, which in education studies can be an important tool in curriculum reform (Crawford et al., 1994; Ebenezer, Kaya, & Kasab, 2018; Prosser, 1994; Prosser et al., 1996).

Participants and Setting

Participants in this study were students at a large, land-grant university enrolled in a junior-level thermodynamics course, which was required for chemical engineering majors. The instructor (second author) had over twenty years of teaching experience and utilized reform pedagogies, emphasizing active learning, concept-based instruction, and regular reflection activities. The course met four times per week, three large class meetings and one smaller sized studio meeting. The large class meetings were interactive and students regularly used an audience response system. In addition to being assessed through the audience response system, there were weekly homework assignments, three Midterm Exams and a Final Exam.

One-hundred and eighty students, mostly chemical engineering majors but a few bioengineering majors, participated in this study. Students were asked to indicate which of multiple social identities they identified with and allowed to choose more than one. Of this group, 52% identified as White Non-Latinx, 28% as at least one racial category other than White Non-Latinx, 61% identified as Male, and 22% as Female. This study was approved by the IRB under study #6981 and all participants provided informed consent.

This study focuses on student responses to a written assignment due in the class immediately following the first Midterm Exam. The examination philosophy was described in the syllabus as follows, "You will be asked to apply the fundamental principles that have been covered in the course to entirely new problems and to answer conceptual questions (questions that are designed to be conceptually challenging and typically require no computation so that you cannot rely on equations to obtain the answer). For the conceptual questions, you will be assessed on your ability to select the correct answer and provide an evidence-based written justification of the choice." The scores for the first exam are typically low; in the year studied, the average was 47.8%, with a standard deviation of 17.4%. The written assignment is provided to help students reflect on the extent that they use rote and conceptual learning operations and adjust their approaches to better align with the course expectations. The instructor had used a similar written assignment in eight previous classes, and those student responses motivated this study. While the specific questions in the assignment were modified in the year the study was conducted, the general categories and themes presented in the detailed analysis are consistent with the responses in the previous years (e.g., Smith, Bowen, Montfort, & Koretsky, 2014).

Data Sources and Collection

The primary data source for this study was the student written responses to the reflection exercise. For the reflection exercise, students were asked to read the article *Another reason that physics students learn by rote* (Elby, 1999), and to answer a set of questions (See Appendix A). In that article, Elby compares how introductory physics students allocate their study time between four categories—concepts, formulas, practice problems, and real-life examples—and how they would advise a hypothetical student, Diana, whose "goal is simply to understand physics more deeply." Elby found that most students focus on practice problems and formulas when studying, as opposed to the real-life examples and concepts which they recommended Diana focus on. Elby concluded that "students study much differently from the way they'd advise someone to study in pursuit of deep understanding" (p. S56), which arises from "an interaction between the habits and beliefs students bring to their introductory college physics classes and their initial experiences in those classes."

The homework assignment consisted of the six questions (Appendix A), and responses were collected electronically. Students' responses to Question 5 were analyzed in this study. Question 5 asks, "In the courses you are taking this term, in what ways is rote learning prompted? In what ways is conceptual learning prompted? (1 paragraph)." In order to elicit students' concrete experience, we situated the question within a comprehensive reflection assignment and asked students to reflect on specific courses that term. The question prompts students to reflect on their learning operations and consider the conditions that lead them to adopt these behaviors. While this question asked students to specifically reflect on the courses that they were currently taking, responses sometimes indicated how rote and conceptual learning operations were prompted throughout their university experience.

Data Analysis

Drawing from Magana et al. (2019), who also used thematic analysis within a phenomenological methodological framework (see also Daly et al., 2012), our analysis consists of the following steps: (1) use thematic analysis to construct a limited number of qualitatively different themes that describe the ways students experience school that lead to rote or to conceptual learning operations; (2) identify the central aspects of these themes including their frequency and affect; (3) characterize the way the different themes connect; (4) identify categories of expanding awareness by consolidating themes; and (5) use network diagrams to characterize the way the different categories and themes contribute to the activity system. This analysis provided data to answer research questions 1 and 2.

In this study, there are two ways we could view the activity system—the course level or the cohort level. Instructors may argue that their individual courses are the appropriate unit of analysis for the activity system. From this perspective, students operate in separate activity systems in separate courses, given that different courses have different rules (grading structures, participation norms) and tools (textbooks, expansive vs. bounded framing). While such a unit is appropriate in many cases, our goal is to uncover students routinized learning operations. Thus, we take the alternative perspective for the unit of the activity system and consider that the collective activity resides at the confluence of the individual courses. We examine responses from a cohort of junior-level chemical engineering students, most of whom are taking the same four required courses and regularly form study groups which stay relatively fixed as they shift from assignment to assignment between courses. We view the unit of activity as the participatory work in these interactions across classes. From this perspective, students work towards a common object using rules that apply to much of the school work that they are doing that term.

The written responses were analyzed using emergent coding and thematic analysis (Braun & Clarke, 2006; Riessman, 2008). Code themes were categorized according to operations of "rote learning" and "conceptual learning," with eight code themes emerging from the "rote" operation and seven code themes emerging from the "conceptual" operation. Given the explicit language used in the prompt, most student responses explicitly stated to which operation a theme was associated. In the few cases when explicit language did not connect a response to a learning operation, we were able to reliably infer the operation given the context of the response. After a stable set of code themes was established, axial coding was conducted (Strauss & Corbin, 1990), and the 15 themes were synthesized into four broader categories: Assignments and Assessment, Content, Classroom Practices, and Educational System. **Tables 1** to **4** summarize the themes that emerged in each category. Some themes exhibited both rote and conceptual operations (e.g., Nature of Problem), while others were only rote (e.g., Reused Problems) or only conceptual (e.g., Group Learning). A single student response could be assigned code themes of both *rote* and *conceptual* operations, as students often described situations where aspects of both rote learning and conceptual learning were prompted.

Table 1: Code list for Assignments and Assessments category.

Code Name	Operation	Definition
Nature of Problem	Rote	The course work exclusively focuses on writing equations and getting numerical solutions, so that just knowing when/how to use an equation is enough to solve the problems in the course.
	Conceptual	The course work contains non-numerical questions (such as explaining assumptions or making predictions) or problems unlike those seen previously (in class/homework/practice exams), which promotes conceptual understanding.
Assessment Prompted	Rote	Exams promote rote learning behaviors since problems can be answered solely by remembering patterns from problems seen previously.
	Conceptual	Exams promote conceptual learning behaviors because answering the problems requires an understanding of concepts, rather than merely "plug and chug" operations.
Reused Problems	Rote	Many problems are similar or identical to previously assigned problems. Instead of understanding the concepts underlying these problems, students state that it is easier to simply memorize the solution path.

Table 2: Code list for Content category.

Code Name	Operation	Definition
Memorizable Material	Rote	The course material is inherently something to be memorized (facts, dates, numbers), but not understood on conceptual level.
Difficulty of Material	Rote	The course material is too challenging to learn conceptually and is easier to learn by rote.
Real World Connections	Conceptual	The course material has problems which relate to the "real world" that promote the integration of underlying concepts.

Table 3: Code list for Classroom Practices category.

Code Name	Operation	Definition
Instructor Emphasis	Rote	Course instructors promote rote learning by what they focus on in lectures. Concepts are explained only briefly or poorly, while problems are heavily emphasized.
	Conceptual	Course instructors promote the understanding of concepts through their classroom approach. Time is allowed to fully explore underlying connections, rather than just deriving equations and solving numerical problems.
Group Learning	Conceptual	Interactions and activities with other students help the student to develop a better conceptual understanding of the material.
Audience Response System	Conceptual	Use of an Audience Response System helps the student develop understanding of key concepts in the course.

Table 4: Code list for Educational System category.

Code Name	Operation	Definition
Importance of Grades	Rote	In order to achieve their desired grade, the student needs to resort to rote learning.
	Conceptual	In order to achieve their desired grade, the student needs to conceptually understanding of the material.
Time Constraint	Rote	The student has other parts of their life (social, personal, and work, including large course workload) and cannot spend time conceptually learning the material. The core belief expressed is that rote learning takes less time than conceptual learning.

Of the 180 responses collected, 11 responses were eliminated. Rather than addressing the question prompt, students instead gave the definitions of each type of learning or simply listed course titles which prompted each type. To ensure inter-rater reliability, a second experienced education researcher coded 30 responses (18%) selected at random using the definitions in **Tables 1–4**. Comparison between the raters resulted in a Cohen's kappa value of 0.76, indicating acceptable inter-rater agreement (Landis & Koch, 1977).

Findings

We present the results in terms of our two main findings. First, student activity, as it relates to student learning operations, is concentrated on the nature of the assignments students are asked to complete and the way they are assessed. Second, the affect with which students describe the ways that rote learning operations are prompted is distinctly different than conceptual learning where anxiety, desperation, resignation, and inevitability are feelings associated with rote learning. The elements for rote operations are more interconnected than those of conceptual learning operations.

In the following sections, we elaborate on the main findings of this study, and support them with evidence of a few select student responses. An important aim of this study is to provide a lens into the student voice. To support this aim, Appendix B presents direct quotations from student responses that clearly exemplify every theme (see **Tables 1–4**). The selected quotations presented here and in Appendix B can be considered exemplary but representative.

Finding 1: Focus on Assignments and Assessments

Our first main finding is that the assignments that instructors ask students to complete and the way students are assessed was the most common focus of students in this study – more than research-based classroom practices or the larger educational system. **Table 5** summarizes the percentage of total responses in each of the four major categories and their corresponding subcategories (see **Tables 1–4**). All categories contained code themes associated with both rote and conceptual operations. The Assignments and Assessments category contained the most responses of any category (73.4% rote and 51.5% conceptual). The Content category had about twice as many responses associated with rote operations as conceptual operations (33.1% rote and 17.1% conceptual). Classroom Practices responses contained mostly conceptual operations (5.3% rote and 34.3% conceptual), and Educational System responses mostly rote operations (38.4% rote and 4.1% conceptual).

The types of problems that an instructor assigns for learning and for assessment appear to be critical in prompting learning operations. Depending on their characteristics, such problems can elicit either rote or conceptual learning operations. Problems that are algorithmic, numeric, and similar to previous problems prompt rote learning operations, as shown below.

> Rote learning might be more promoted when every single question on the midterm is based off of formulas. To be honest, sometimes it is hard to distinguish between me understanding the material and me redoing the practice problems over and over again until I can repeat it even with minor changes to the problem. *[Nature of Problem: Rote, Reused Problems, Assessment Prompted: Rote]*

In this response, elements of the Assignments and Assessments are noted as factors that influence the student's use of rote or conceptual learning operations. Rote learning operations are associated with some ambiguity towards learning, as this student describes difficulty in distinguishing between their "understanding the material" and "redoing the practice problem over and over" until they can "repeat it."

On the other hand, problems that emphasize critical thinking, consideration of assumptions, require identification of information not given, or have multiple possible answers elicit conceptual learning operations. In short, problems that are crafted in ways to promote sense making and associations to other knowledge lead to conceptual learning operations. The following student identifies how problem design can prompt conceptual learning operations:

Table 5: Summary of coding results for the each of the categories and subcategories as percentage of responses (n = 169).

Category Name	Percent of Total Responses		Subcategory Name	Percent of Total Responses	
	Rote	Conceptual		Rote	Conceptual
Assignments and Assessments	73.4	51.5	Nature of Problem	49.7	42.0
			Assessment Prompted	39.6	23.1
			Reused Problems	21.3	–
Content	33.1	17.2	Memorizable Material	27.8	–
			Difficulty of Material	8.9	–
			Real World Connections	–	17.2
Classroom Practices	5.3	34.3	Instructor Emphasis	5.3	18.3
			Group Learning	–	13.0
			Audience Response System	–	10.7
Educational System	38.4	4.1	Importance of Grades	24.3	4.1
			Time Constraint	24.9	–

> For example, in [course title], we recently had to calculate the difference in heat transfer for a stegosaurus with and without fins. Obviously, stegosaurus' aren't around anymore and there is no data on this. This forces us as students to use our understanding to use reasonable assumptions and concepts to come up with a reasonable solution. *[Nature of Problems: Conceptual]*

The idea of coming up with a "reasonable solution" is indicative of a problem that is viewed as having several acceptable solutions rather than a single right answer. In this response, this student articulates that rather than memorizing patterns, they need to operationalize their understanding through "reasonable assumptions and concepts," that is, use conceptual learning operations.

As **Table 5** illustrates, classroom practices, particularly those incorporating active learning, were mostly associated with prompting conceptual learning operations. Specific pedagogical strategies mentioned by this cohort included collaborative group learning and formative assessment using audience response systems. While students view these practices as contributing positively to conceptual learning operations, they were identified in less than half the number of responses as Assignments and Assessments. Instructors who were open to questions and readily explained and emphasized concepts were also cited as promoting conceptual learning operations; conversely, instructors who do not explicitly value and model conceptual understanding discourage students from using conceptual learning operations.

Finding 2: Strong Affect Associated with the Educational System

The second main finding is that the elements associated with rote learning formed a more connected network than elements associated with conceptual learning. Importantly, the responses that suggested the educational system prompts rote learning (about one-third of the total) were characterized by a strong affect. They contained language indicative of anxiety, desperation, resignation, and inevitability. Students commonly expressed a lack of agency and indicated that they had no choice other than to resort to rote learning operations. We first present network diagrams for rote and conceptual learning operations to illustrate the extent to which themes were connected in the student responses and then illustrate the difference in affect with representative quotations.

Figures 2 and **3** show network diagrams for rote learning operations and conceptual learning operations, respectively. In each diagram, the four major categories are represented by different colors; Assignments and Assessments is blue; Content is purple; Classroom Practices is green; and Educational System is brown. The circles, hereafter called nodes, represent the code themes in the network and are sized in proportion to the number of responses attributed to that theme. For example, the most common response in **Figure 2**, Nature of the Problem, was identified in 84 out of 169 student responses and is represented by the largest circle. The connections between the nodes, known as edges, show the cases where both themes were coded within a particular response and are also sized in proportion to the number. For example, 32 out of 169 students whose response was coded for Nature of the Problem in **Figure 2** were also coded with Assessment Prompted while 19 were also coded with Importance of Grades. The relative density of edges between nodes is a measure of the interconnectedness of the themes in each network. The density is obtained by dividing the total edge count (e.g., 283 in **Figure 2**) by the

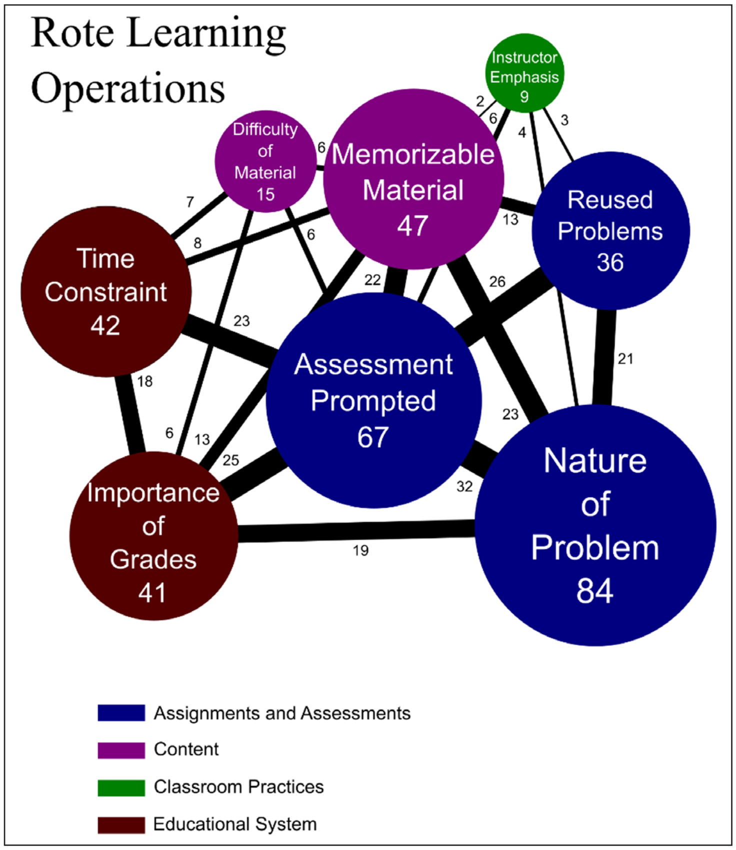

Figure 2: Network diagram for code themes of rote learning operations. The nodes are colored according to the four general categories, and the nodes and edges are sized in proportion to the number of responses.

product of the number of themes (eight themes in **Figure 2**) times the total theme count (341 in **Figure 2**), yielding values of 0.104 and 0.064 for rote and conceptual operations, respectively. By this measure, the rote learning operation network is more connected than the conceptual learning operation network.

Elements of the Educational System are an important element in the rote learning operations network (**Figure 2**) with students referring to the Importance of Grades and to their Time Constraints. These themes are connected in 48 out of 67 instances of the Assessment Prompted subcategory of Assignments and Assessments. Conversely, there is only slight appearance of Classroom Practices in the rote operations network (nine out of 169 responses) where types of Instructor Emphasis that focused on single answers to algorithmic and numeric problems were related to rote learning operations.

Similarly, responses in the conceptual learning operations network (**Figure 3**) tied most commonly to Assignments and Assessments but they connected differently to the other themes identified. The most prevalent ties connected them to Classroom Practices such as Instructor Emphasis, Group Learning, and Audience Response System. These practices provide framing and activities that support conceptual learning operations. Content with Real World Connections also prompts these operations. Unlike rote learning operations, there were infrequent connections to the Educational System.

From the perspective of the rote learning network view illustrated in **Figure 2**, we could envision a disproportionate weight of the educational system influencing those students who passionately cite it. This *gravitational pull* of the educational system is strengthened since the edge connection density is greater for the rote network than the conceptual learning operations network (**Figure 3**). To further corroborate the pull of the Educational System on student learning operations, we present select quotations from student responses.

Students expressed feeling constrained by a large workload, arguing that more time is required to conceptually learn the material, and pressured to achieve sufficient grades to pursue their professional aspirations, exemplified below.

> I know that I truly want the deep understanding but I'm so afraid of getting mediocre grades and not looking good for internships, scholarships, and employment. *[Importance of Grades: Rote]*

Similar to many rote operation responses, this student describes a sense of anxiety and inevitably based on tensions between objects (a "deep understanding" vs. grades) in their activity system of doing school. This student describes obtaining deep understanding as something which they "truly want," but also as detrimental to their academic success, leading to

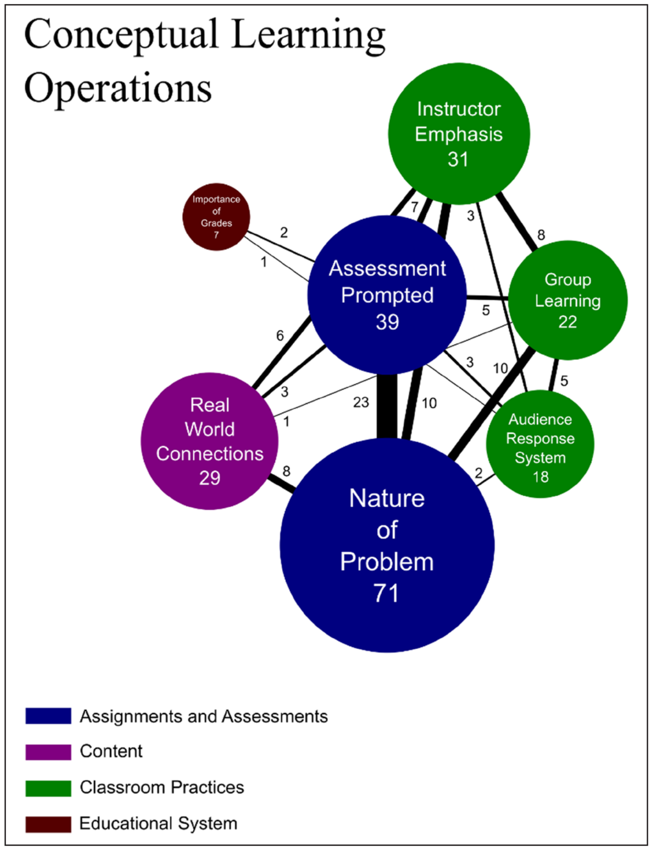

Figure 3: Network diagram for code themes of conceptual learning operations. The nodes are colored according to the four general categories, and the nodes and edges are sized in proportion to the number of responses.

"mediocre grades," and missed career opportunities. Other responses also described a perceived connection between rote learning operations and higher performance scores, with students believing that using these operations are the best way to succeed. Responses often expressed high levels of despair and inevitability, as illustrated by examples in Appendix B.

Conversely, responses coded for conceptual learning operations usually contained matter-of-fact language, with those few that displayed affect being positive and more understated than those associated with the educational system, a illustrated in the following response.

> On the other hand, [course title] promotes conceptual learning because it is impossible to do well on the exams without a good understanding of the concepts. *[Importance of Grades: Conceptual]*

Discussion

This study focuses on identifying and explicating the elements that prompt students to use either rote or conceptual learning operations through the holistic lens of activity systems. We analyzed the responses of a cohort of junior level chemical engineering students to a written assignment after the first midterm examination where they reflected on their study approaches. Importantly, the study design provided access to the *student voice*. We identified themes and corresponding categories that emerged from their responses, and illustrated them with direct quotations. From a situative perspective, these data suggest ways that students are unconsciously prompted to utilize rote or conceptual operations to study. The operations are conditioned by, and thereby expose, salient elements of the activity system that these students, their instructors, and other community members participate in while doing school, as well as the ways in which these elements are interconnected. We elaborate on the two main findings below. We then describe how an activity systems perspective can help reconcile some incongruous results in the literature and discuss the limitations of this study.

Finding 1: Focus on Assignments and Assessments

The first main finding was that assignments and assessments were by far the most frequently cited elements in the students' activity system. They can prompt either rote or conceptual learning operations. This finding aligns with similar calls in the engineering community for shifts in the curriculum towards more realistic work. For example, two National Academy of Engineering reports (2004, 2012) look at how realistic work will enable engineering graduates to better meet the evolving needs of the profession. We add to this literature by fundamentally looking at how a cohort of engineering students engaged in their studies. Our study contributes an additional and important connection—that the type of assignments and assessments can fundamentally influence the orientation students have towards their learning. We believe that shifting more students to conceptual learning operations is critical to forming connected and adaptable knowledge to meet the goals of those National Academy reports. To our knowledge, this connection has not been addressed in the engineering education literature.

This class sits within a curriculum in which students have had several prior courses that include both studio-based collaborative learning and regular use of audience response systems; thus, these student-centered instructional practices are familiar and a normal part of instruction. We interpret this result to indicate that student-centered classroom practice can support conceptual learning operations and should be encouraged, but only to the degree that those instructional practices align with the other work students are asked to complete and are evaluated on. While we support the engineering education research community's exuberance to shift to active learning classroom practices (Borrego, Cutler, Prince, Henderson, & Froyd, 2013; Borrego & Henderson, 2014), caution should be taken to make sure ample attention is also given to aligning homework assignments and assessment when promoting those practices. Importantly, exam questions should be consistent with homework assignments and other class activities in eliciting and assessing these ways of thinking.

Finding 2: Strong Affect Associated with the Educational System

The second main finding was that the elements that prompt rote learning operations are more connected than those that prompt conceptual learning operations. Importantly, students who cite the educational system as promoting rote learning operations regularly display strong, negative affect. Drawing from Leander and Brown (1999), this result implies that the strong affect felt due to the educational system coupled with other elements in the students' highly connected rote learning network can lead to disengagement. This result suggests innovative ways to decrease the emphasis on grades and give students more time for sense-making as they work should be considered as important strategies to improve retention and graduation rates.

Jaber and Hammer (2015, 2016) have introduced the construct of the *epistemic affect,* the emotions associated with the practice of doing science. They argue that professional scientists feel a sense of excitement associated with uncertainty and a desire to pursue the unknown and resolve problems, that these feelings are an inextricable part of being a scientist, and that they can and should also be part of learning science in school. In particular, a recent case study (Radoff, Jaber, & Hammer, 2019) describes a university physics class that used an instructional design that aligned with elements identified in our study that elicit conceptual learning operations—a focus on everyday thinking using interactive classroom practices with assignments and assessments that contained uncertainty but rewarded sense-making and being thoughtful, even when the answer is wrong. The study reports an environmental engineering student, Marya, transformed from anxiously seeking single right answers by algorithmically manipulating equations to taking pleasure in sense-making and actually enjoying the uncertainty associated with real problems. We find the shift in this student's experience compelling. We conclude that by shifting activity from doing school to doing science or engineering (see also Engle and Conant, 2002), we may replace the negative affect we found from students immersed in an Educational System promoting rote learning operations to the positive affect reflected by Marya's participation in scientific thinking. As discussed above, such a shift requires changing the nature of the assignments students complete and how they are assessed. More research is needed on the development of class work that promotes authentic disciplinary thinking in engineering classes and the ways that work can shift feelings associated with students' school experience. Moreover, educators interested in organizational change around teaching and instruction should explicitly address the ways their planned initiatives change students' affect in activity.

Interpretation of the Literature

Finally, an activity system perspective helps reconcile some of the disparate results of studies that have related classroom practices to the deep versus surface learning approaches that students' report. Redesigned classrooms which implemented problem-based learning, collaborative learning activities, simulations and games, or encouraged discussions of case studies have often been found to *deepen* students' learning (Gordon & Debus, 2002; Sivan, Leung, Woon, & Kember, 2000; Tiwari et al., 2006). However, other studies have found redesigned classrooms to increase *surface* learning strategies (Nijhuis, Segers, & Gijselaers, 2005), and others still showed redesigned courses have mixed effects (Balasooriya, Toohey, & Hughes, 2009). In addition, several researchers have reported that deep and surface approaches to learning do not correlate with quantitative learning assessments (Asikainen, 2013; Lizzio, 2001; Trigwell & Prosser, 1991). These researchers suggest that deep learning improves *qualitative learning outcomes* such as understanding and transferability.

Such variability in research findings aligns with the concept that students' approaches result from a set of interconnected elements within an activity system. New instructional practices introduce new tools into the learning environment. Tensions are created in the system when shifts in tools, such as the implementation of a new instructional practice, force students to shift their actions in response. Ideally, changing the nature of instructional practices would lead the students to shift towards conceptual learning operations. However, sometimes the opposite occurs. The rote learning operation network illustrated in **Figure 2** shows connections between every theme found in this study; thus, any change in a single element in the system (e.g., a particular instructional practice) may reverberate to those interconnected aspects of activity that are connected to it. For example, if the changing instructional practices conflict with the nature of assignments and assessments given, it will be less likely for a student to shift orientation towards conceptual learning operations. In contrast, assignments and assessments may be geared to address the students' capacity to show proficiency on concepts rather than just procedures, that is, they may reflect *qualitative outcomes* rather than just assess their ability to *do school.*

Educators have championed a more holistic approach to instructional design, such as backwards design (Wiggins & McTighe, 2005) and idea-based learning (Hansen, 2011). Instructional design begins with identifying the core concepts and big ideas for students to learn in the course, then appropriate assessments and instructional practices that support learning these concepts follow. For example, in the class studied here, regular formative assessment with audience response systems was geared towards concept-oriented questions (Beatty, Gerace, Leonard, & Dufresne, 2005). Similarly, these types of questions were included on exams. We applaud these student-centered designs and believe they align with practices that support conceptual learning operations identified in this study. In addition, we suggest it is fruitful for instructors take a step back to extend beyond their course boundaries and consider (to the extent possible) the activity system of their students doing school. Such a perspective attends to both the other courses that students may be taking and the out-of-class activities that occupy a student's life while doing school.

Limitations and Trustworthiness

This study has several limitations and the findings should be considered with these limitations in mind. The data that were analyzed was collected from one cohort of engineering students from a single assignment in one class. In addition, while making the study methodologically tractable, we acknowledge that the coding of distinct rote or conceptual learning operations creates a false binary similar to surface and deep learning. It is reasonable to assert that there are rote aspects to conceptual understanding—as that thinking has to rely on some core declarative knowledge. Thus, we do not mean to imply that conceptual learning operations are without any element of rote, but rather we are concerned with learning environments that encourage students to rely exclusively on rote operations. School activities exclusively prompting memorization and pattern matching are both unproductive and stressful.

Within these limitations, there are several ways that we ensured the trustworthiness that allows transferability to other settings. First, an entire cohort was given the opportunity to participate in the study and most provided valid responses; thus, the corpus of data is representative of that group. Second, the second author has been using a similar reflection activity for many years, and the qualitative findings from this study generally align with those experiences. In fact, two such assignments were delivered while this article was being written, and the student responses were consistent with the findings reported here. Third, the coding scheme was verified by a second researcher and an acceptable measure of interrater reliability was achieved.

Implications

Within the cultural activity of doing school, the types of assignments and assessments that students encounter are by far the most frequently cited element in this study in prompting them to activate either rote or conceptual learning operations. In short, while students recognize student-centered classroom practices as encouraging conceptual learning, they focus more on homework, projects, and exams. In addition, while not cited as frequently, elements of the educational system, especially time constraints and the importance of grades, discourage conceptual learning operations. Importantly, the language associated with the educational system suggest despair and inevitability and communicate a level of severity not found in any of the other responses.

We call on instructors and administrators to reflect holistically on the elements within their school's activity system and actively shift them to promote conceptual learning operations. For example, consider the following scenario: an administrator learns that shifting to *student-centered* pedagogies, such as flipped classrooms, results in better performance and, therefore, higher retention and graduation rates. The administrator supports a change initiative for faculty to adopt flipped classrooms, with active learning exercises during class time, and supports a two-day summer workshop for faculty to learn how to flip their class. Without further guidance, a set of faculty flip their classrooms, incorporating group learning activities and audience response systems during the traditional lecture periods. However, assessments and homework assignments do not change from years past, leading students still rely on rote learning operations, such as found by Eley (1992), and no quantitative improvement in assessment performance is recorded. This scenario highlights the interconnected and multifaceted activity system in which students *do school.*

It is critical for instructors to spend time ensuring their assignments, exams, grading, and feedback practices align with conceptual learning operations. Assessments designed to promote critical thinking rather than algorithmic problem solving using plug-and-chug strategies are needed. Particularly, providing students new situations that promote activation of concepts from previous activities or problems, using qualitative problems that emphasize scientific reasoning, and requiring students to identify and justify assumptions and calculations are all recognized by students as beneficial. As one student wrote, "tests [that promote conceptual learning operations] ask questions similar enough to things we've seen before that they don't provoke a, let's say fear response, but put in enough twists that a real understanding of engineering concepts is required." In addition, instructors should avoid reusing problems on exams, whether that be from practice exams, previous years' exams, or homework problems, as students can be tempted to pattern seek, thus promoting their adoption of rote learning operations.

Creating these types of assignments and exams is challenging and the required effort needs to be recognized and rewarded. Instructors can utilize model approaches and specific content that are available within the engineering education community such as from projects supported by the National Science Foundation in the Engineering Education Coalition Program in the 1990s (Coward, Ailes, & Bardon, 2000) to the Revolutionizing Engineering Departments (RED) program in the 2010s and 2020s (Lord et al., 2017). For example, ongoing RED projects that include novel assignments and assessments that shift the cultural activity of doing school include:

- *Design challenges* at the University of New Mexico use tasks that are aligned with global engineering problems, such as health (Oden, Mirabal, Epstein, & Kortum, 2010), and replace traditional quizzes and homework that cover given topics (James, Svihla, & Qiu, 2018);
- In *knowledge integration* at Colorado State University, educators are weaving together core concepts from multiple courses in order to solve real-world engineering problems and allow students to see how concepts learned in individual courses are interconnected with those in other courses and used in a professional setting (Maciejewski et al., 2017); and
- *Studio 2.0* at Oregon State University situates students as professional engineers working in teams on open-ended design problems in a flipped classroom design. A typical problem might explain a situation where a company is seeking to optimize a particular process and ask the team to collaboratively develop a design recommendation. Assessment focuses on whether teams are making progress rather than obtaining the correct answer (Koretsky et al., 2018).

These examples illustrate ways to shift the activity system of *doing school* to one which promotes the use of conceptual learning operations.

Classroom practices are also important. Using collaborative learning and formative assessment and framing class activity in terms of conceptual understanding support conceptual learning operations. However, instructors may get limited benefit to incorporating these practices unless the course's assignments and assessments align with this learning approach. More research is needed on these interactions between classroom practices and type of assignments and assessments. From the perspective presented in this article, learning operations, rote or conceptual, are tacit and routinized. Reflection activities, like the assignment reported in Appendix A, should be included regularly and discussed to make these operations visible to students. As they become visible, students can take actions to intentionally shift their learning orientations.

To promote student success, administrators should recognize the role of the connected aspects of the activity system as well as its history. Student experiences draw from a system that often places a high value on acquiring grades by recalling and reciting information, and from the relative ease of routinized memorization techniques. About one-third of the students expressed being helpless to direct their learning towards conceptual understanding in light of time limitations, the importance of grades, or both. It is reasonable to think that these students are at greater risk for leaving the program and the university, and that those who do persist will not be as prepared to activate that knowledge in their professional, civic, and personal lives. Administrators need to conceive of creative ways to shift the educational system to relieve these pressures. For example, in programs where a cohort takes multiple required courses in the same term, administrators could facilitate ways to coordinate scheduling of exams, projects, and homework and for collective faculty evaluation of the student workload. Administrators can also incentivize faculty interaction and dialog so that students receive more consistent messages that support conceptual learning operations. In regards to evaluation of instruction, there is an increasing effort to assess and reward research-based classroom practices (DeMonbrun et al., 2017; Smith, Jones, Gilbert, & Wieman, 2013). These efforts are valuable, but there should also be corresponding efforts to assess and reward the types of assignments and assessments that are used in a class to ensure they also align with conceptual learning operations. Researchers need to identify classification schemes and practices for such evaluation.

Appendix A

Reflection exercise used in this study

Read the following paper: Elby, A. (1999). Another reason that physics students learn by rote. American Journal of Physics, 67, S52. https://doi.org/10.1119/1.19081

Answer the following set of questions:

1) In your own words, define rote learning. (1–2 sentences) Define conceptual learning. (1–2 sentences)
2) In the context of this study, what is the author's definition of distortion? How does the author measure distortion? (2–3 sentences)
3) In section IV, the author contends physics students are rewarded by rote learning. In what ways are physics students rewarded? (1 paragraph)
4) Do you agree with the author's main points? Explain. (1 paragraph)
5) In the courses you are taking this term, in what ways is rote learning prompted? In what ways is conceptual learning prompted? (1 paragraph)
6) How have the classes you have taken prepared you for your career in engineering? (1 paragraph)

Appendix B

Example student responses for all themes

An important contribution of this study is that it focuses on listening to the student voice and relating that voice to how students experience the activity of doing school. Tables B1–B4 show illustrative examples of quotations with identified themes provided in brackets at the end of the quotation. Many responses show multiple connected themes as illustrated for the cohort in Figures 2 and 3.

The student response for the subcategory Time Constraint – Rote is particularly concerning. They reference isolating themselves from "almost everything," concerns about their family, and being blamed by an instructor for not studying enough after reading "the book and notes" and "many articles" on the subject matter, suggestive of unrealistic expectations by the instructor. The use of rhetorical questions throughout the quotation and the statement in all capital letters that "in order to SURVIVE this term, I have to use rote learning," indicate the depth of the student's anxiety and lack of agency in their adoption of rote learning operations. These feelings of desperation and inevitability were rampant and particularly strong, though not so extreme as this example, in the responses coded for Educational System themes.

Table B1: Response Examples for Assignments and Assessments category.

Code Name	Operation	Example
Nature of Problem	Rote	"Rote learning might be more promoted when every single question on the midterm is based off of formulas. To be honest, sometimes it is hard to distinguish between me understanding the material and me redoing the practice problems over and over again until I can repeat it even with minor changes to the problem." *[Partial| Nature of Problem: Rote, Reused Problems, Assessment Prompted: Rote]*
	Conceptual	"[Course title] does a great job in prompting conceptual learning! Conceptual learning is promoted through homework questions and test questions where you don't have to look at a formula sheet as much and you instead need to consider all the concepts you've learned and how they apply to a new problem." *[Partial| Nature of Problem: Conceptual, Reused Problems, Assessment Prompted: Conceptual]*
Assessment Prompted	Rote	"Rote learning is prompted in the courses where exams make up an overwhelming majority of the grade for the course. An example of this is my [course title] course. The course grade boils down to how well I do in two one hour exams, and one two hour final. I don't have time to think about how to solve the problems because any time wasted means that I won't finish, and will fail. Instead I have to complete practice problem after practice problem to try and have a preprepared answer in my brain for whatever I will be asked to solve" [*Assessment Prompted: Rote, Importance of Grades: Rote, Time Constraint*]
	Conceptual	"Conceptual learning tends to be prompted by midterms and finals that contain qualitative questions in which students must use their understanding of different properties to predict what will occur in a system and explain why they believe in their prediction." [*Assessment Prompted: Conceptual, Nature of Problems: Conceptual*]
Reused Problems	Rote	"... the test is bound to be on a problem you should have seen somewhere before. It becomes a game of trying to memorize as much as you can in the hopes that you won't fail too badly." [*Assessment Prompted: Rote, Reused Problems*]

Table B2: Response Examples for Content category.

Code Name	Operation	Example
Memorizable Material	Rote	"For instance, in my [course title] course, it is all about memorizing amino acids, cycles, cell structures, and proteins and since there is not recitation or lab, I feel as though I am prompted simply to memorize everything and perform on the test. I can tell you every step of the citric acid cycle, but only vaguely understand its importance. This saddens me because I am a BioEngineer and I want to work in the field of genetic research, where knowing these concepts would be immensely helpful, but I am told that I need to go to graduate school to get an understanding and undergraduate is simply to memorize the generalities and move on." [*Memorizable Material*, *Assessment Prompted: Rote*]
Difficulty of Material	Rote	"This class is also very difficult to understand conceptually, and the formulas are much easier to memorize when and how to apply rather than understanding the reasoning behind them." [*Difficulty of Material, Memorizable Material*]
Real World Connections	Conceptual	"… being asked to solve real-world problems with numbers or information NOT provided. First go-to is conceptual understanding of the situation, rather than skimming through a textbook chapter in search of a solution algorithm (which wouldn't exist anyway)." [*Real World Connections*, *Nature of Problems: Conceptual*]

Table B3: Response Examples for Classroom Practices category.

Code Name	Operation	Example
Instructor Emphasis	Rote	"There are classes like [course title] that seem like there aren't even any concepts it's just specific problems to solve. It's very hard to learn conceptual points when the professors do not even stress it or talk about why something is happening. When the professor doesn't stress that type of learning, it's hard for the student to really want to spend the time to learn the answer to why something is happening." [*Instructor Emphasis: Rote, Nature of Problems: Rote*]
	Conceptual	**"**The formulas are presented and explained well (what variables mean what), but the professor makes a point to explain the physical phenomena behind any assumptions being made and why those assumptions have an effect on the formula. Problems to work on during class are also utilized to test a mix of mathematical understanding and conceptual understanding. While working on these problems, any questions can be asked of peers or the professor about confusion regarding any physical phenomena present." [*Instructor Emphasis: Conceptual, Nature of Problem: Conceptual, Group Learning*]
Group Learning	Conceptual	"I especially like it when students in the class explain why the answer is what it is because they usually do it in a way that makes sense to me, probably because they have a similar knowledge base as me." [*Group Learning*]
Audience Response System	Conceptual	In terms of conceptual learning, I absolutely love [Audience Response System] because it helps me understand the ideas/concepts presented and not even bother looking at the math calculation of it. You use the knowledge you have to answer the question, you work in groups, and at the end the answer is revealed and explained which allows me to recalibrate my thinking. [*Partial quote\Audience Response System, Group Learning*]

Table B4: Response Examples for Educational System category.

Code Name	Operation	Example
Importance of Grades	Rote	"I know that I truly want the deep understanding but I'm so afraid of getting mediocre grades and not looking good for internships, scholarships, and employment." [*Importance of Grades: Rote*]
	Conceptual	"On the other hand, [course title] promotes conceptual learning because it is impossible to do well on the exams without a good understanding of the concepts." [*Importance of Grades: Conceptual*]

(Contd.)

Code Name	Operation	Example
Time Constraint	Rote	"... I isolate myself from almost everything, during the weekdays, I just do homework and study and I got the gym and that it. If my family who I used to call them every other day know that there is something wrong with myself because calling them since I am super busy with school. I want to learn and I knew since 8 years ago that being a chemical engineer will require a lot of sacrifices and a lot of long nights without sleep. But, what is happening this term is upnormal. For example, I am taking [course title] this term which is a very hard course. The professor usually blames us that we don't study and we don't spend enough time. the course is so hard and If I spend all of my time on it, what am I gonna do with the other 3 courses ? I went to him and I asked him a question after I read the book and notes and read many articles on [subject] and I asked him a question from the book. The answer was that I did not study very well and I need to spend more time. I told him that I can't spend more time because I am taking other course than he replied that it is not his fault, I have to deal with that. what shell I do more than I am already doing? quit sleep and spend 24 hr studying? what I am trying to say is that in order to SURVIVE this term, I have to use rote learning. Because if I am gonna use conceptual learning, I will not pass any of my class and I will not have time to do homework problems that is assigned every day." [*Time Constraint*, *Importance of Grades: Rote*, *Assessment Prompted: Rote, Difficulty of Material*]

Reproducibility
Individual anonymized student responses and coded data for question 5 are available by contacting the second author.

Ethics and Consent
This study was approved by the IRB under study #6981 and all participants provided informed consent.

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Competing Interests
The authors have no competing interests to declare.

Author Contributions
Dr. Edward Michor led the literature review of approaches to learning and performed the iterations of data analysis; Dr. Milo Koretsky conceived the study, developed the theoretical framework, and collected the data; both authors collaborated on the data interpretation, and drafting and revising of the submitted manuscript.

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