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Identification of Students' Epistemological Frames in Engineering

Christina Smith, Oregon State University

Christina Smith is a graduate student in the School of Chemical, Biological, and Environmental Engineering at Oregon State University. She received her B.S. from the University of Utah in chemical engineering and is pursuing her PhD also in chemical engineering with an emphasis on engineering education. Her research interests include diffusion of innovations and student personal epistemology.

Alec Bowen, Oregon State University

Alec Bowen is an undergraduate in Chemical Engineering at Oregon State University and expects to receive his B.S. in June 2014. His research focuses on engineering education, particularly in student personal epistemology and the development and utilization of educational simulations.

Dr. Devlin Montfort, Oregon State University

Devlin Montfort is an Assistant Professor in the School of Chemical, Biological, Environmental Engineering at Oregon State University. His research interests include the theoretical, methodological, and philosophical peculiarities of conceptual change and personal epistemology in the context of engineering education and practice. He holds a Ph.D. in Civil Engineering from Washington State University.

Dr. Milo Koretsky, Oregon State University

Milo Koretsky is a Professor of Chemical Engineering at Oregon State University. He received his B.S. and M.S. degrees from UC San Diego and his Ph.D. from UC Berkeley, all in Chemical Engineering. He currently has research activity in areas related engineering education and is interested in integrating technology into effective educational practices and in promoting the use of higher-level cognitive skills in engineering problem solving. His research interests particularly focus on what prevents students from being able to integrate and extend the knowledge developed in specific courses in the core curriculum to the more complex, authentic problems and projects they face as professionals. Dr. Koretsky is one of the founding members of the Center for Lifelong STEM Education Research at OSU.

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Introduction

Understanding how a student frames or interprets a learning experience gives insight into how students approach learning and why they employ certain study habits. If a student's personal epistemology, or how she/he views learning and knowing, does not align with an instructor's pedagogy, it could undermine efforts to engage students in active learning environments. By characterizing students' personal epistemologies along a spectrum and understanding the differing views, we can address their views of learning and improve student learning.

We adopt the view suggested by Hammer and Elby that personal epistemologies are manifold constructs that consist of fine-grained elements called *resources*. When networks of resources are activated and reinforce one another, they can become stable and form belief-like structures called *frames*. This approach to personal epistemology therefore makes strong links between students' epistemologies and the courses they are engaged in because those courses provide the background contexts in which resources and frames are activated. Hammer and Elby argue that this framework of resources "shows generativity and explanatory power, especially for understanding variability in a student's behavior"[1(p409)] because it leads to more "nuanced judgments about the epistemological productivity of that behavior." [1(p422)] In a learning environment, a student's epistemological frame influences how she/he interprets and approaches learning activities and it plays a critical role in how the student experiences that context. By identifying frames and subsequently resources, educators can identify strategies to help students build more productive approaches to learning.[1(p416)]

There have been several studies on student personal epistemologies conducted within the Science, Technology, Engineering and Mathematics (STEM) fields, with the bulk of the work done in physics and mathematics.[2–4] Although there have been studies conducted in the realm of engineering,[5–7] there is a need for a more in-depth analysis of student epistemologies that consider the vital role of context. This study addresses that need by using qualitative analysis, combined with Hammer and Elby's framework of frames and resources, to explore how undergraduate chemical engineering students frame their experience in the context of a junior level thermodynamics course that uses concept based instruction. As a context for investigating student epistemologies this course is particularly rich because students are explicitly encouraged to examine how their study habits support or obstruct success in the course.

This study analyzes students' open-ended written responses to an assignment asking them to reflect on learning and performance in their engineering courses. We posed the following research questions:

1. Within the context of this assignment, how do students explain what it means to (i) gain understanding and (ii) perform well in engineering?
2. What specific epistemological frames are evident in student responses? How do the frames differ based on differing views of performance in engineering?

Background

Personal epistemology has been defined as "the set of beliefs that individuals hold about the nature of knowledge and its production".[8] Hofer and Pintrich[9] agree with this definition, which does not include the nature of learning; however Hofer also recognizes that personal epistemology has a "powerful influence on learning".[10] In response to this influence, Elby argued that personal epistemology should not be so exclusive in its definition and should also include views on learning if the data suggests that it is "inseparably entangled with views about learning".[11(p139)] We approach our analysis open to this possibility and, within the context of this study, seek to characterize the degree to which views of the nature of knowing and learning might be intertwined.

There have been a wide variety of studies conducted on how students approach knowledge and learning. These studies can be divided into three general categories modeled by how each one approached epistemology. One group investigated how individuals interpret their experiences,[12–14] another how epistemology influences reasoning and thinking processes,[15,16] and more recently that epistemology is a system of beliefs or independent cognitive structures that can form belief like structures.[17,18] In each of these studies, researchers indicate that there is a growth in epistemology from a more naïve epistemology to one that is more sophisticated. Hofer and Pintrich[9] present a more extensive review of each of these models.

These models come from the fields of educational psychology, mathematics, and physics, and more recently an interest has emerged in the field of engineering education. Douglas, Koro-Ljungberg and Borrego investigated the role of epistemology and methodology in engineering education and found that "the present authors [had] not been able to identify any discussions of the role of epistemology in engineering education"[19(p248)] expressing a need for a better understanding of engineering epistemologies. In a special report conducted by the Steering Committee of National Engineering Education Research Colloquies, engineering epistemologies is one of five research areas for the new discipline of engineering education.[20] This decision also suggests that a better understanding of student approaches to knowing and learning is important to prepare future engineers. To address these concerns, Yu and Strobel developed an instrument assessing epistemological as well as epistemic and ontological beliefs.[6,7] Carberry, Ohland, and Swan[5] developed the Epistemological Beliefs Assessment for Engineering (EBAE) aimed at quantitatively measuring students' engineering epistemological beliefs. From the standpoint of frames and resources, any discussion of 'predictors' would have to include descriptions of the common and pervasive educational contexts that repeatedly activate specific frames and resources. Eventually, once the link between context and epistemology is better understood, students' personal epistemologies could be 'predicted' based on the educational contexts they find themselves in.

Overall there is very little work investigating personal epistemology in engineering education, with the majority of that work using surveys as the primary source of data. We argue that personal epistemologies develop within complex social systems and are subject to individual's experiences and perceptions and that surveys do not allow an in-depth look into these complexities. This study attempts to fill this gap by investigating students' personal epistemologies in a specific and rich context: their views of learning in a particular course. The study was done using a qualitative approach by analyzing written student short-answer responses to a writing prompt, capturing a large group of students that might not otherwise be possible with most in-depth interview methodologies.

Theoretical Framework

In this paper we adopt the framework put forth by Hammer and Elby[17] and treat personal epistemologies as manifold constructs that individuals apply subconsciously in response to particular social contexts and circumstances, and therefore are highly context dependent. Within this framework, Hammer and Elby[17] suggest that instead of individuals holding epistemological beliefs, which are solidified and declarative knowledge constructs that can be consciously accessed, they instead hold epistemological *frames* made up of epistemological *resources.* These resources are fine-grained knowledge elements representing primitive forms of epistemological stances that become activated under certain contexts and conditions. When a set of resources is activated, reinforced by one another, and stabilized, they form belief-like structures called *frames*. Frames are belief-like in that they can be perceived as a distinct epistemological stance. However, unlike epistemological beliefs, these frames are stable in part because of the context. A change in context could have a dramatic effect on the frame because a different set of resources could be activated. For example, a student who exhibits a sophisticated epistemological frame towards gaining knowledge in a history class may exhibit a naive one in a biology class. One challenge that the resources framework presents is that resources are difficult to identify because more than one are typically activated and therefore the "main observable grain-size...corresponds to an epistemological frame."[1(p409)] For this reason, we focused on identifying epistemological frames from the student responses.

Methodology

This study was a qualitative study investigating open-ended written responses to a prompt that asked students about rote learning in their engineering courses.

Participants and Setting

Students for this study came from two cohorts of a junior level thermodynamics course at a large land grant university. All students who had signed an IRB informed consent form were selected to be participants (n=158). Active learning and concept-based instruction are emphasized in this course. Immediately following the first midterm, students were given a homework assignment asking them to read *Another reason that physics students learn by rote* by Andrew Elby.[21] In this article, Elby used a two-part questionnaire to survey 106 introductory college physics students asking them about their study habits. The first part asked students how they distributed their time between formulas, concepts, practice problems and real-life examples, followed by questions about their study habits and preferences. In the second part, students were then asked the same questions about a hypothetical student, Diana, whose grade did not matter in the course she was taking. Students were asked how she should spend her study time between formulas, concepts, practice problems and real-life examples, and to explain why she should study this way. The focus of Elby's study was to investigate distortion, or the difference between what students indicated were their personal study habits compared to how they would tell a student who cares only about understanding to study, reflecting on their epistemological beliefs. Elby found that most students study differently, focusing on formulas and practice problems rather than on concepts and real-life examples, than how they would tell someone else who is trying to acquire a "deep understanding."[21(pS56)] He concludes that "[s]tudents perceive 'trying to understand physics deeply' to be a different activity from 'pursuing good grades'..." as one result of students believing rote learning is sufficient enough to obtain high grades.[21(pS56)]

Data Sources and Collection

Responses to the Elby assignment were collected through an online instructional tool.[22] Students were asked the following questions in this assignment:

1. What does the author mean by epistemological beliefs? (1-2 sentences)
2. In the context of this study, what is the author's definition of distortion? (1-2 sentences)
3. How does the author measure distortion? (1-2 sentences)
4. What is the main point of this paper? (1 paragraph)
5. In section IV, the author contends students are rewarded by rote learning. In what ways are physics students rewarded? Do you believe your engineering classes reward rote learning in a similar way? Support your position. (2 paragraphs)

Responses from question 5 were analyzed for this study because it asked students to reflect on and interpret their own experiences. These responses naturally provide a window into their epistemological resources and frames. The intent for the first four questions is to provide a common basis for such a reflection. Furthermore, questions 5 was broken up into two parts, which generally allowed us to differentiate between when the student expressed their ideas on physics and engineering. Responses to the first part were generally summary statements, often including the student's definition or interpretation of rote and conceptual learning. In addition, student answers to this part provided information about what students understood learning to mean. This information was taken into consideration while analyzing the second part focused on engineering, which allowed us to compare and contrast views of how students learn and perform in engineering classes. The majority of the responses indicated that the students were aware of the different learning environments of physics and engineering.

Data Analysis

Applying the Hammer and Elby framework of epistemological *resources* and *frames*,[17] we used emergent coding and thematic analysis[23] to identify themes and possible resources and frames within the student responses. Initially, we used resources that Hammer and Elby identified to guide our development of themes for our coding process, such as 'knowledge as propagated stuff' or 'knowledge as constructed.'[17(p178)] We then investigated possible frames students had about learning in engineering as well as what learning methods they perceived as effective. Of the 158 responses collected, 148 were coded based on the themes determined from this process. These responses were then coded using a qualitative coding program. Two researchers coded the responses independently and through an iterative process, used Cohen's Kappa to determine the reliability of the coding process. The remaining 10 responses did not contain enough information to apply the themes and codes.

Themes that were identified while coding included the type of learning (rote, conceptual, or both) the student viewed as best suited for: (i) gaining understanding (*Learning*), (ii) grade performance (*Performance),* (iii) and which they chose to employ (*I Choose*). Each response was coded for all three theme types. These themes were put into a *Learning, Performance, I Choose (LPIC)* combination based on the student responses. For example, a combination could include: I believe the best way to gain an understanding is through conceptual learning, but rote memorization is rewarded so I choose to do rote. Definitions for each theme of *Learning, Performance,* and *I Choose* were used by both coders with a description of each below. The majority of responses were explicit in what the student thought about each theme, however we did look for keywords such as “most” or “majority” to indicate a preference of a student. When a student used the word “some” followed by an explanation, we coded that response as “both.” Of the 148 responses coded, 124 of them had an agreed upon *LPIC* combination by two researchers.

Learning (L)
We looked for general and specific descriptions of what the student believed it meant to learn. These descriptions typically appeared in response to the first part of question 5, in which students explained how physics students are rewarded by rote learning.

Performance (P)
In addition to learning, we also examined which learning method students thought was best for classroom performance. In the prompt, students were asked if they believed their engineering courses rewarded rote learning in a similar way to physics. Student answers to this question gave us information on what they see as effective learning methods in the classroom based on how it was being rewarded.

I Choose (IC)
Students who explicitly stated the learning method they chose to employ in engineering classes were coded under the *I Choose* theme. To be given a code, a student had to make it clear that she/he was talking about her/himself and not about students in general. Students who did not clearly state what learning method they use in engineering classes, or only referred to students in general without explicitly stating that they were speaking of themselves, were given a code of *no strong indication*. We did this to focus on student’s personal epistemology instead of a perception of what that student thought her/his peers’ epistemologies were.

Results and Discussion

Research Question 1: Within the context of this assignment, how do students explain what it means to (i) gain understanding and (ii) perform well in engineering?

Examples of the *LPIC* combination coding process are given below with full response examples given in Table 1. This coding resulted in a Cohen’s Kappa of 0.78 through an iterative coding process.

Learning (L)
These explanations were usually accompanied by an implicit definition of rote learning as memorization, which was then contrasted with learning as understanding. These responses were coded as “learning is conceptual,” such as:

> “In engineering classes conceptual learning is the best way to learn the material, understanding the concepts will help you derive the correct equation for the unique problem you are faced with.”

Only two students indicated that rote memorization was a good way to learn. In both cases, it was accompanied with a statement about how rote learning should be used in conjunction with conceptual learning and was coded as ‘both.’

Performance (P)

Most students were explicit in answering this question because it was asked for specifically in the prompt, for example:

> “I believe engineering classes reward rote learning because after reading this article, I see myself as someone who doesn't always strive to grasp a deep conceptual understanding, however I am still able to obtain high grades.”

These students referenced grades, homework, or class structure as rewards and influences for the different types of learning. A more in depth discussion of this theme is presented under Research Question 2.

I Choose (IC)

Approximately 30% of students explicitly stated the learning method they choose to employ. An example of a student who chose to learn by rote stated:

> “most of the time I spend for example is trying to do the homework rather to take time to study learn my material in a more deeper way *(sic)*”

and a student who chose to learn conceptually:

> “I don't believe that my engineering classes reward rote, they tend to be based around theory and deep concepts. I can no longer get away with a mediocre understanding of the material. It's especially difficult because many of the equations we use now need to be derived based on the situation.”

Results of coding the responses into *LPIC* combinations indicated that there is a discrepancy between what how students believe they develop understanding and what they see as being rewarded in class. As Figure 1 show, 98% of the students responses indicate they believe that conceptual learning is the best way to learn; however, a majority also believe that rote learning (52%) or both conceptual and rote learning (34%) is rewarded in their classes. Of those who responded on how they chose to learn, approximately half explicitly stated that they chose to learn conceptually with the other half choosing rote. We assumed that if a student expressed that they believed that both *Learning* and *Performance* were conceptual, they chose to learn conceptually.

This evidence shows that students are aware that a conceptual approach to learning is a better way to understand the material in class, however they see that rote learning is rewarded and therefore many choose rote learning. Students approach learning how they see it being rewarded. An example of this view is shown as follows:

Table 1. Full response examples for different *Learning, Performance, I Choose (LPIC)* combinations

L	P	IC	Example
C*	***R***		"While rote learning may sometimes achieve the reward of better grades, it rarely rewards the students of a better understanding of the material. However, I believe that the way the school system is currently set up, rote learning is rewarded favorably over conceptual learning. While a conceptual learning style would be favorable on exams if the concepts were allowed to be solidified in students' minds, 10-week terms packed to the brim with engineering work does not allow time for some conceptual learners to attain confidence with the concepts. These students are then quickly overwhelmed and forced to conform to a rote style of learning, which is both frustrating and difficult."
C	***R***	***R***	"I believe that engineering courses reward rote learning in a similar way because I usually spend my time on studying for exams by reviewing homework problems since I believe that exam problems mirror the homework problems. I also study recitation problems as well as example problems presented in lecture. As far as concepts go, I always try my best to look at the conceptual side of a subject but when it comes to studying for exams, I focus my efforts on looking at formulas and working on problems. This means that my study habits are distorted so that I can earn a good grade in the class. If I didn't feel to pressure to be successful in a course, I would want to develop a deeper understanding of the subject of the course by applying the concepts to real-life situations."
C	***C***	***C***	"Rote learning is not rewarded from my experiences in engineering courses. I feel, professors are always emphasizing us to have a deeper intuition. However, quite a bit of the homework can be completed using rote learning. The best I have done in an engineering class is when I have had a deep conceptual understanding of the concepts. The reason being, I struggled less during tests. *(sic)*"
C	***B***		"I believe that my engineering classes, along with many others, sometimes reward rote learning in a similar way, but not always. Usually exams are a mixture of quantitative and qualitative questions; the rote learner will usually only understand quantitative questions. It is the nature of the beast, as exams are of course going to have quantitative problems, and students are usually loaded with many classes at once and do not have the time to develop truly deep understanding of all classes given the fast pace and large load of homework, studying, and exams of complex material. I believe that all students, even those who develop a deep understanding, use rote learning to some extent. *(sic)*"
C	***B***	***R***	"As I started this year I made it a goal for myself that I would try and learn the actual concepts because I have made it into pro-school and I dont aspire to go to grad school. So far I have realized that if I would have learned concepts better the previous 3 years, I would have more time to learn new concepts now. Instead, just recently I have had to switch back to efficiency of my time. While I still believe our program allows rote learning, they seem to try harder than any other professors Ive had elsewhere to have us learn concepts. I see a lot more conceptual and out-of-the ordinary test/hw questions from CBEE than in other courses. *(sic)*"

*C= conceptual, R= rote, B= both

"I believe that the majority of my engineering classes reward rote learning in a similar way. A lot of the work done in my engineering courses utilizes equations to find a wanted value. I know what each variable of an equation represent and this allows me to just "plug-and-chug" until I get an answer. I can follow how an equation is derived, but I do not fully comprehend what the equations are usually telling me. At the end of the course, I feel as though I have a remote idea of the material, but not really a clear understanding. However, the next term comes around and I do not feel I have the time to try and learn it on my own. *(sic)*"

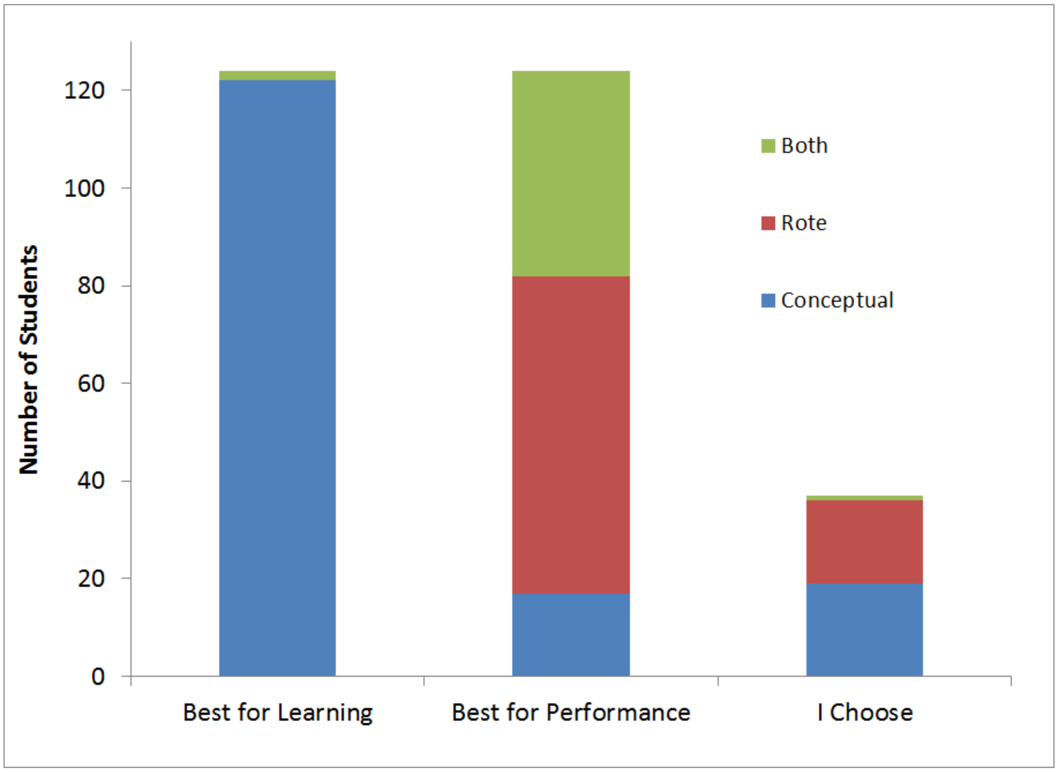

Figure 1. Plot of how students view learning type, rote, conceptual and both, as best for *Learning* and *Performance*, and what some students chose (*I Choose)*

In this statement, the student comments on the use of equations as a vehicle to find a right numerical answer. However, she/he also recognizes that equations are more than just variables and that there is a level of understanding the student doesn't have time to learn on her/his own. The time component may be an indication that the student views learning as happening individually, but the recognition that equations are more than just variables suggests a slightly more sophisticated epistemological frame. This response conveys that for this student, learning conceptually is not an option because they don't have the time to do it. These were themes that were present in many student responses.

Another student expressed:

> "Most of my engineering classes thus far have awarded rote learning. Many of the quizzes are reflections of questions on homework rather than purely new material and many lectures are 50 minutes of recording equations that all exist in the book… I would prefer to have a more complete understanding of the material I am learning, but the time constraints I face cause me to try and get assignments done quickly rather than fully absorb the material. These time constraints are the main reason that I believe rote learning is as popular as it is."

This student explicitly believes that time is the reason that students employ rote learning. Time was a very prominent theme present in many of student responses that believed *Performance* was rewarded by rote, and is explored more in depth in answering Research Question 2. This student also sees rote learning being rewarded through the assessment and structure of the class, which are activities that students engage in frequently. She/he does not appear to find value in the lectures because what is presented in class is available in her/his book. This is an interesting epistemological view because it places knowledge coming from a source, or an authority.[12,14] There is a conflict with epistemological views and practice, made apparent in the "I would prefer…" statement. These themes also occurred in several responses.

In contrast, an example of a student who believed that conceptual learning was rewarded stated:

> "I am sure that engineering classes reward a rote learning of the material to some extent, but I think it is to less of a degree as other courses. Most engineering tests I have had (so far) have been open note or open textbook. This means I don't need to memorize the "formulas" (if there is such a thing) to solve a problem. For the most part, the hurdle is conceptualizing the situation and formulating a solution path. Once that is done, the formulas and derivations follow. (You can still memorize "solution paths" for problem types, though I don't know if this is really rote-learning or just good practice.)..."

Again, the role of equations or formulas is important to how this student approaches learning. Instead of worrying about finding equations and solutions, this student understands that her/his goal is to find a solution path. This results in her/him then able to develop the formulas. This approach to learning is very different than the students who expressed there is an expected right or wrong answer to every problem: a solution path versus a solution. This response also touches on the theme that rote learning is reinforced through assessment. This theme is also further explored in Research Question 2.

The following response incorporates two different views on what is expected to know and do in engineering based on her/his year in school, comparing this difference between solution and solution path:

> "Most of the engineering classes do reward students for this kind [rote] of learning. The problem most of the credit and focus is around tests. Most of engineering is the ability to provide a number, weather it is the size of a reactor or how much product can be produced. Because of this need for a number the easiest way to get a number is to plug and chug with a known equation. Easy becomes very necessary when you start getting into harder classes and you get more of them. As time becomes limited understanding priority is quickly exceeded by just get it done and getting a good grade on it… *(sic)*"

The student continues:

> "This is less true in my senior, mostly because there is not a "right" answer. Some answers are better than others and this is mostly determined based on thing that

> you would never see if you just plugged through questions. One of the biggest changes is that assumptions are no longer given to use and we need to understand in order to know what we can assume. In prior classes, especially those before pro school, your assumptions were give to you, so you could go straight to an equations and go. Without those assumptions there is no equation or at least not one you can reasonably solve. Rote learning comes from the concept that there is a right answer and easy way to get it…*(sic)*"

This is an interesting response, because the student starts by stating that "most" of engineering requires a number as a final solution, which would be viewed as a naive epistemological frame. However, she/he continues to state that as she/he has progressed through school, there is more than one answer with some proving to be better than others. The difference between pre-engineering courses (freshman and sophomore) and "pro-engineering" courses (junior and senior) was a theme found in many student responses and also indicates that a student's personal epistemological frame is context dependent. This was also a main indicator that the student believed that performance was rewarded by both a rote and conceptual approach. What is interesting is that students recognize a difference between lower and upper division courses. The students for this study were in a junior level thermodynamics course and many expressed they wished they had learned material using a conceptual approach prior to this course. This indicates that bringing attention to students' personal epistemologies earlier on their undergraduate career may prove beneficial in helping them to develop more productive epistemologies.

Along this theme, the following two examples also show cases where students believe that learning is conceptual and performance is rewarded by both, but one chose to learn by a conceptual approach and the other resorted to rote learning.

The student who chose a conceptual approach stated:

> "Students are rewarded by grades. GPA is the currency of academia (other than my tuition that is) and rote learning can often be the best way to get high marks on exams.
>
> I think that some lower division engineering courses reward rote learning, particularly when exams are based on formulaic answers. If you have memorized what numbers go where, you can solve the problems without a deeper understanding. This does not help with all exams, however, and even less so in upper division. I feel that upper division courses do not reward rote learning because engineering is all about reasonable assumptions and approximations. Making those reasonable assumptions requires knowledge of what the equations represent, and that knowledge is very difficult to develop without a deeper understanding of the mechanics behind the numbers. With my learning style in particular, I have a very hard time using an equation unless I understand why I am using it, so I don't employ rote learning very often."

There is a strong frame present that assessment is the driving factor for rote learning. This student also interprets the difference between rote and conceptual learning through the different use of equations in lower and upper division courses. How students use and view equations is a frame that gives us insight into how a student values conceptual knowledge and how they believe knowledge is constructed. Students who see equations and formulas as a series of variables given to produce a solution may view knowledge as disconnected and discrete, a naive epistemological frame. If a student recognizes that an equation is an embodiment of a scientific principle, they also understand that knowledge is interconnected and builds on other knowledge.

In the following example, the student realizes much later in her/his academic carrier that learning the concepts would lower the activation energy for learning related concepts. This view is in part because she/he believed that the academic environment was more conducive to this mode of studying. This excerpt is also reminiscent of other responses where students state that they had approached learning through rote memorization since elementary to high school, and that it is hard to get out of the habit.

> "...I spent the first couple years of college getting by using the rote learning style because I thought everything I was taking was only a way to weed students out of pro-school.
> As I started this year I made it a goal for myself that I would try and learn the actual concepts because I have made it into pro-school and I don't aspire to go to grad school. So far I have realized that if I would have learned concepts better the previous 3 years, I would have more time to learn new concepts now. Instead, just recently I have had to switch back to efficiency of my time… *(sic)*"

Research Question 2: What specific epistemological frames are evident in student responses? How do the frames differ based on differing view of performance in engineering?

After becoming well acquainted with the data and variety of views of the *Performance* category, we wanted to further explore the themes that had emerged from this category. We broke up *Performance* into each type of learning: rote, conceptual, both, to code for themes. For this portion of analysis, all agreed upon *Performance* responses were used, regardless if the researchers differed in the other two categories of *Learning* and *I Choose.*

To answer this question, we identified recurring themes based on coded responses in the *Performance* category. See Table 2 for the common themes identified.

Table 2. Prominent themes found from student responses based on *Performance* type

Performance rewarded	**Themes**
Rote	(1) An exclusive classroom focus on equations and formulas leads to rote memorization. (2) Time is too limited to gain a conceptual understanding and do well in the class. (3) Students are rewarded for rote learning because they can scan through the textbook to find relevant problems and equations. (4) Rote learning is easier. It can get the same grade but with less effort. (5) Students have been learning by rote since elementary school. It is how they do things. (6) There are recurring problem types that can be memorized for the test and guarantee that students do well.

Conceptual	(1) Open book tests mean rote is not rewarded. (2) Problems require a deep understanding to do correctly. (3) Mathematical modeling requires a deep understanding. Equations are too complex to simply memorize. (4) Material builds on each other. (5) Partial credit on exams promotes conceptual learning. (6) You must be able to solve new and unique problems. (7) Studios and recitations give students the chance to learn conceptually.
Both	(1) There is a difference between pre-engineering (freshman, sophomore) and pro-school (junior, senior) classes. (2) Pro-school does not reward rote, while pre-engineering classes do. (3) How much a class rewards rote depends entirely on the instructor. (4) How much a class rewards rote depends entirely on the material. Some classes simply have a greater focus on computation. (5) Classes are a mixture of rote and conceptual learning. Some parts require a deep understanding, while others only need rote memorization. (6) Tests are open book so they don't reward rote learning. (7) Creating mathematical models from data and assumptions requires conceptual understanding.

These themes were then interpreted to develop frames about how students might view performance in engineering. An overview of preliminary frames identified is given in Table 3. We chose two frames in particular to investigate further because they were very common and represented the bulk of the data for each learning style: (i) rote is more efficient for performance than conceptual learning and (ii) rote understanding is reinforced with assessment, with a final Cohen's Kappa of 0.77 and 0.83 respectively.

Table 3. Identified frames from student responses

	Frame	**Coder Definition**
Rote	**Rote is more efficient for performance than conceptual learning**	Student states that rote takes less time for studying, is more efficient, or is easier than conceptual. It is more efficient because it can reduce workload and the time spent on problems (test or homework).
	Rote understanding is reinforced with assessment	Student mentions tests, homework, grades or the structure of these assessments as a reason why they do rote learning. Should be a clear connection between the two. Rote learning lets students do at least as well on tests as if they had learned conceptually.
	Rote understanding is reinforced by learning environment	Student talks about the structure of the class, studios/recitation, the instructor, or the overall institution. This frame is more holistic than reinforcement through assessment. Examples include: this is how they've been doing it for years, time is a reason why they haven't been instructed or they have a large workload due to other classes, or school grades have always been important.

	Rote understanding is reinforced by material (content)	Student states that equations and formulas, looking through the book, the material of the course are why/how they use rote learning. Might also mentioned how engineering is different from other courses e.g. math, chemistry, etc.
	Equations are memorized, not understood	Student indicates that equations are taught, but not understood. She/he need equations to learn but don't understand the underlying concepts.
Conceptual	Conceptual understanding is required for flexible application (effective problem solving)	Student indicates that conceptual understanding is needed to solve a variety of problems in different situations.
	Conceptual understanding is reinforced with assessment	Student mentions conceptual learning is reinforced through tests, homework, or grades. There is a clear connection between assessment and learning type.
	Conceptual understanding is reinforced by learning environment	Student talks about the structure of the course, how the instructor teaches, or indicates conceptual learning is important in other courses.
	Conceptual understanding is reinforced by material (content)	Student indicates that material builds on itself
	Equations are understood, not memorized	Student states that you need to conceptually understand an equation in order to use it, equations shouldn't/can't just be memorized.
	Knowledge has an interconnected structure	Student indicates that knowledge builds, mentions using concepts from multiple classes

Rote is more efficient for performance than conceptual learning

Responses coded for this frame included a statement saying that rote learning allows students to do homework, study, and take tests in less time than conceptual learning. Some examples of this frame are:

> "When it comes down to it, time constraints will always make the students lean towards rote learning because it will help them the most on the test. It will be hard to change learning styles when one reaches the college level and have been doing the same thing all your life."

> "Rote learning is the most efficient way to get assignments done. It is much easier to find an equation in the book than it is to understand the equation."

> "It takes a lot less time to learn the math and formulas than to actually understand what we are learning. It also, unfortunately, leads to better grades."

Many students in this group said that they learn by rote out of necessity; there is too much classwork to learn everything conceptually:

> "There is simply not enough time to come to a deep understanding in each class when students have multiple homework assignments, exams, quizzes, and extracurricular activities each week. There has to be some sort of time management in place to get everything done and maintain sanity and this generally comes at the expense of deeper learning."

> "Often times, I'll hunt down equations that look useful, use them to solve the problem, and see if my answer looks reasonable. Then I'll ask in hindsight Ok, why did or didn't this approach work." I believe I approach homework problems this way because my time is limited, and while I want to have a strong conceptual understanding of everything I do, sometimes I just need to have an answer to turn in so I can move onto my other projects."

They use rote problem solving techniques to get through problems more quickly in order to be prepared for tests. Through many of these responses, students reference equations and formulas and the role they play in their study habits and learning style. From this come two other frames: equations are memorized, not understood and conversely equations are understood not memorized. Within these two frames, students can either activate the *knowledge as propagated* or *knowledge is constructed* resources,[17] implicating a naive or sophisticated epistemology respectively. Expanding from equations, other students stated that by memorizing certain problem solving techniques, they are able to complete tests in the time allotted:

> "Many of our homework assignments can be completed without fully understanding the conceptual problem. This also extends to our tests. For the tests specifically I feel this is especially true for us due to the intense time pressure we are put under many times. This stress many times means a brute force method of recalling memorized formulas or situations is the first thing to be applied. This is because under the time pressure it is many times difficult to comfortably take the time to contemplate and unwrap a problem conceptually, especially when doing so could punish you later when you run out of time doing calculations (which many times are extensive)."

The resources *knowledge as propagated* or *knowledge is constructed* could be extended to *solutions as propagated* and *solutions as constructed.* We can contrast this statement with the student in Research Question 1 that thought class performance rewarded conceptual learning, who believed that a solution path came first, which was then followed by the equations and formulas. Students that fell into this *rote is more efficient* frame generally saw knowledge as linearly acquired and did not see the material and concepts as interconnected.

A different perspective is to look at how rote learning affects the instructor's time:

> "Especially in classes that are large it is also a time consuming task for professors/TA's to grade all of the material and if conceptual questions are given then each grading of the question is somewhat subject to opinion of the grader, leading to students complaining for unfair grading policies who are deeply concerned with maintaining a high GPA… Thus to streamline the system,

questions based on a clear cut answer (number solution) are the most common forms of questions and given time constraints with due to the workload of other classes, produces a truncation in the learning process for students who in most cases simply want to pass the class."

Rote understanding is reinforced through assessment

Responses coded for this frame included a statement about how rote learning is rewarded in classrooms by allowing students to achieve good grades. Sometimes the students would explain by saying that they use rote memorization techniques when preparing for and taking tests, and they get good grades while doing it. For example, here is one student response:

> "Am i rewarded like the physics students? Yes, because I have gotten by with good grades even without fully understanding mass and energy balance, fluid transfer and thermodynamics conceptually. In a desperate situation I try to apply a problem to another without turning to conceptual reasoning and most often it works! *(sic)*"

Others specifically state that the only way to get good grades on tests is through rote memorization:

> "Whether or not a student wishes to deeply understand a subject, rote learning and practice problems are necessary to do well in stressed, calculation based exams"

Still others say that the homework and test design is set up to reward rote learning:

> "Yes I do believe that many of the engineering classes that we take encourage rote learning. A lot of professors like to assign problems that are very similar to the homework so the more you go over the same homework problems the more likely you are to just spit it all back up on the test and get a good grade in the class. *(sic)*"

This single frame can be further broken down into component frames. Tests, homework, grades, etc. either require students to learn by rote, or they encourage students to do so. This means that students think classes assess knowledge that has been transferred rather than constructed; instructors do not differentiate between transferred knowledge and constructed knowledge when assigning grades. This frame was common amongst both rote and conceptually oriented students, so assessment perceived by instructors to be a good indication of learning may not align with the students' perceptions of what learning means or is valued. Awareness of this frame provides a prompt to instructors to consider if they should present and approach assessment differently.

Conclusions and Implications

Student personal epistemologies are complex. They are the result of their cummulative experiences and vary with each student and context. This study aimed to provide more detail into how students view what it meant to learn and perform in engineering through analyzing student written responses. We identified that students understand that learning conceptually is better than rote memorization, but have mixed views on how classes reward different types of learning.

Based on how students viewed what was the best way for performance in engineering, we characterized different epistemological frames students may have when reflecting on their courses. These included: rote is more efficient for performance than conceptual learning, rote understanding is reinforced with assessment, conceptual understanding is required for flexible application, and knowledge has an interconnected structure. There is a need to look at these frames from a finer-grain size of resources. Understanding resources is important because once instructors are aware of what resources students are activating, they will be able to provide guidance for their students to more productive epistemological frames through different pedagogical practices and through interpersonal interactions.

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