Learning Statics: A Cognitive Approach

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Abstract - The deficiency in conceptual understanding among students in statics courses has been well-documented [Steif, 12, Steif, 13, Streveler, 15]. Recently, much progress has been made in identifying, quantifying, and treating the misconceptions that students bring with them to the course, and this research provides valuable insights to professors teaching these concepts. It is argued here, however, that also needed are better ways of organizing and delivering course content in order to promote the transfer of material to new contexts as well as the development of metacognitive abilities in students [Bransford, 5, Greeno, 7]. Through the analysis of survey and interview data collected from statics students during the spring 2009 semester at a large public technical university, this pilot study identifies further opportunities for research aimed at promoting deeper understanding of course concepts in statics. The results show that even after course material was presented, practiced in homework problems, and tested in an exam, some students struggled with transfer of these concepts to new situations and lacked the metacognitive ability to successfully monitor their progress when solving problems. While students in general were confident in their ability to perform the math required for the course efficiently, those interviewed showed difficulty describing course concepts and the interrelations among them. Moreover, the individual ways that the interviewed students approached learning in this course seemed to hint at potential explanations for differences in their performance. While the results of this pilot study are not sufficient to prove any such relationship between learning approaches and performance, they do provide indication of potentially fruitful areas to explore further. Additionally, they may highlight the need for a cognitive approach to course design and administration with activities that promote meaningful connection among course material rather than solely mathematical proficiency. Thus, this paper proposes curriculum enhancement through application of modern educational research, specifically outlining some possible activities that align with cognitive theories of conceptual learning.

Keywords:statics, cognitive learning theory, metacognition

LITERATURE REVIEW

Past and Current Thinking about Learning – An Overview

In recent years, much work has been done in the study of human learning. Indeed, since its scientific roots in the lab experiments conducted by Thorndike, Watson, Skinner, and others in the early 1900s, our understanding of how humans learn has greatly evolved, drawing on the resources of countless scientists representing several scientific fields ranging from philosophy to neuroscience [Alexander, 1, Bransford, 5]. Perhaps the most influential change seen over the course of the past 100 years is the birth of cognitive theories of learning, which departed from the behaviorist tradition of viewing learning as responses to stimuli and the development of associations between them; instead, cognitivism focused on learning as the development of internal concepts and ways of organizing, storing, and processing information in the mind [Greeno, 7]. More recently, however, has been the emergence of a new view of learning, termed situative or sociocultural, that sees learning as a social process of participation and becoming accustomed to the ways in which knowledge is used in genuine contexts. Each of these views brings their own sets of benefits, limitations, and implications for teaching.

Much of the current instructional methods in statics can be traced to behaviorist origins although efforts are being made by some to include other forms of learning as well. Learning by “practicing” skills in the form of graded homework problems and textbook examples as well as a highly structured curriculum that requires mastery of elementary tasks before moving to more difficult problems (i.e., finding force resultants before considering forces on particles and eventually bodies) are two prominent examples of current behaviorist practices. Some cognitive

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approaches have been incorporated into statics classrooms, including concept questions and hands-on activities designed to help students conceptualize notions of forces, moments, and others through physical interactions with objects [Steif, 14]; the effectiveness of these interventions has not been fully assessed, however. Regardless, such approaches may be enhanced and expanded through greater collaboration with and use of the findings from researchers in the learning sciences, particularly educational psychologists and instructional technologists. Situative approaches are not currently seen in mainstream statics instruction, likely due to feasibility issues relating to typically large class sizes and requirements for individualized assessment, but examples of such approaches may include students working alongside practicing engineers or upperclassmen on projects involving statics concepts.

How Should Learning Be Viewed? - The Debate Continues

With our ever-changing understanding of how human learning takes place, debate continues amongst educational psychologists about the scientific support for each approach. Recent discussion revolves around the theoretical divide between the cognitive and situative positions (for the most part, it seems that there is general agreement on the benefits and limitations involved with the behaviorist perspective). In particular, situativists criticize cognitivists for taking the mind model too far, isolating it in an effort to study it closely and explain its functions but in doing so removing it from the environment from which it operates and "confus[ing] our representations with the phenomenon we are modeling" [Clancey, 1991 as cited in Alexander, 1]. Cognitivists, on the other hand, question the situative theory's ability to result in feasible educational applications; questions remain about ways of offerings students in typical schools legitimate participation in the everyday activities of professionals and perhaps more importantly, how to assess their learning [Greeno, 7]. These claims can be seen in the continuing dialogue between the primary supporters of each side as well as the devotion of a recent special issue of *Educational Psychologist* to the search for common ground between the competing theories [Anderson, 3, Anderson, 4, Greeno, 8, Mason, 10].

Despite the ongoing conflict, many scholars on both sides of the issue have made progress in reconciling the two viewpoints [Mason, 10]. Many cognitivists see the benefit and necessity of taking into account external factors and social interactions that undoubtedly play a role in learning; similarly, many situativists see benefit in representing knowledge structures in the individual mind as well as the external world. The result has been the development of theories along a continuum as Alexander presents in her work (See Figure 1), and while behaviorism does not appear on her model, one may not completely discount empirical evidence for its existence. In fact, a growing view of scholars is that elements from each theory can play an important role in our understanding of human learning. As Bredo describes in the most recent Handbook of Educational Psychology, "Although each new model or metaphor, or each new level of analysis—genetic, individual, socio-cultural, or some other—adds something to our understanding, each is limited." [Alexander, 1]. Educators, then, must decide on which approach(es) are most appropriate for the learning objectives of their course, keeping in mind the realistic constraints of their particular school environment.

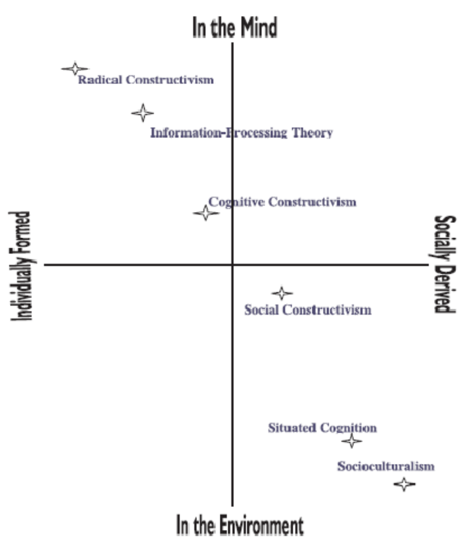

Figure 1. Continuum of Situative/Cognitive Learning Theories [As given in Alexander, 2]

Certainly in statics courses (and mechanics courses in general), there are a range of objectives that may be taught more effectively with certain approaches. Behaviorist theories may be well-suited for objectives involving memorization, recall, or discrimination, where reinforcement and conditioning can provide an efficient way of learning the "factual knowledge" that is needed for higher levels of learning in the discipline. Trigonometric relationships, correct units for certain physical quantities, constants of gravitational acceleration, solving systems of equations, and others are all items that may be efficiently taught using behaviorist principles; this allows for minimal cognitive processing by students [Ertmer, 6], who may easily get discouraged if otherwise required to learn in-depth the derivations of these elements. However, many of the higher level thinking skills and, indeed, much of the actual "statics" knowledge that we expect students to learn while in the course cannot be done through behaviorist methods alone, as they would require too much time and would not provide the structure that students need to build their knowledge upon in subsequent classes. Cognitivist methods, including concept mapping, building on prior knowledge, misconception identification and correction, and others may be better able to support objectives that require analysis or synthesis of foundational knowledge. Such objectives may include drawing free body diagrams, analyzing the interaction between and within bodies, and understanding the role of statics in a larger context. The situative perspective can also play a role in knowledge development in statics courses (and more broadly in mechanics courses) although no current methods have been reported that may be applicable to the existing course structure. Situative learning can occur, however, through undergraduate research, internships, and other similar experiences.

Learning Occurs Everywhere - The Role of School in Education

Today, human learning is studied in diverse settings using innovative methodologies to reveal how learning takes place implicitly, informally, and formally. In their discussion of these three areas of research in the Handbook of Educational Psychology (Chapter 10), Bransford et al. argue for the need for researchers in each of these areas to engage in collaboration and discussion around "conceptual collisions" in an effort to unify these three often unlinked strands of research [Alexander, 1]. If this call for collaboration is answered, it may provide a better understanding of the learning process as a whole; however, for now at least, educators will likely continue to focus on methods of improving formal learning.

Central to the design of formal instruction remains the selection of appropriate learning theories as discussed previously, which bring with them the benefits and limitations inherent in each. However, it is the view of this author, based on the review of current work in the area of learning theory, that at present, the cognitive perspective provides the most promising findings and applications to educational practice. Indeed, Calfee points out that "cognition remains the discipline's [educational psychology] prominent paradigm" [Alexander, 1]. Thus, it will be reviewed here in more depth. One would of course be remiss, however, not to keep in mind opportunities to draw on the expanded ways of knowing and learning that arise from other learning theories.

The Cognitive Goal - Transitioning from Novice to Expert

Regardless of learning theory used, a common goal of formal instruction is the growth and development of student knowledge, taking students from the novice level of performance towards that of an expert, someone proficient in the practice of the discipline. For cognitivists, an expert is someone with considerable knowledge that is highly structured around key concepts [Alexander, 1]. This structure allows them to more easily recall related groups of knowledge, processing them in working memory more efficiently than as disconnected facts, which in turn frees up cognitive resources to focus on other aspects of a problem [Bransford, 5]. Experts are also able to look beyond the surface features of a problem that novices tend to focus on, making them better at problem solving and understanding although perhaps less skilled at making evident to learners their thought processes along the way [Alexander, 1]. Adaptive experts are those who use their knowledge efficiently and innovatively, as opposed to routine experts who hone specific abilities; thus, the transition from novice to adaptive expert is not a one-dimensional process and we must encourage growth in both areas for students if they are to progress toward this goal. Along these lines, Streveler et al. [Streveler, 15] point out several research questions that have yet to be investigated in engineering subjects like statics, primarily surrounding issues of what novice to expert transition looks like and how knowledge structures change during transition. While the answers to these questions would undoubtedly help robust curriculum development and should be pursued by researchers, there may be other implications from cognitive theory that may facilitate formal learning that can be implemented by instructors right now.

Promoting Transition - What Must our Instruction Accomplish?

Questions remain about the best practices for promoting transition in students engaged in formal learning. However, modern cognitivists widely agree on a few key research findings that may have important implications for teaching and certainly deserve attention. First is the role of prior knowledge that affects how students learn in the classroom and misconceptions that they may form. Research identifying misconceptions in statics and methods that may be used to build conceptual understanding around these difficult concepts is currently the work of some in the field [Streveler, 15]. Another area is the development of metacognitive abilities in students. Metacognition, the ability to monitor one's own progress while problem solving and learning, is a trait commonly seen in individuals further along the novice-expert continuum. These skills are crucial to courses like statics that set the conceptual framework for future mechanics knowledge.

METHODS AND RESULTS

Background of the Pilot Study

During the spring 2009 semester, a pilot study was conducted to investigate potential areas for future research related to improving student conceptual knowledge and performance in courses like statics. Specifically, the study aimed to identify potential cognitive barriers that may inhibit learning and application of the material. Study participants were all enrolled in a single section of a statics course at a large public technical university; the class consisted of approximately 250 enrolled students.

Survey

A survey was administered to the students to collect self-reported class data on several areas of interest:

- Previous enrollment in Statics courses
- Hours spent per week working on statics outside of class
- Level of mastery with selected prerequisite content prior to the start of the semester:
    - Trigonometry (right triangle trigonometry, similar triangles, Law of Sines and Cosines, etc.)
    - Vector Expression (creating vectors from given scalars, angles, points, etc.)
    - Vector Algebra (manipulating vectors using addition, subtraction, dot products, cross products, etc.)
- Confidence in current performance ability in selected course content areas:
    - Resolving vectors and moments in 2 dimensions
    - Resolving vectors and moments in 3 dimensions
    - Creating 2-dimensional equilibrium equations
    - Creating 3-dimensional equilibrium equations

Likert-type scales were used for the level of mastery and confidence entries, ranging from very poor (1) to excellent (7) and extremely unconfident (1) to extremely confident (7), respectively. The survey was designed to look for possible links between a student's math prerequisite knowledge and their current ability to perform statics problems; this is known to be one area that potentially results in poor student performance in statics. Differences in the confidences of students who had previous classroom exposure in statics content were also sought out. Finally, the survey was used to screen for interview volunteers. The survey was distributed in class at about the midway point during the semester, after all selected course content areas had been presented and tested; participation was voluntary, confidential, and in accordance with local IRB standards.

Interviews

Interviews were developed and conducted after survey data collection but prior to data analysis. To efficiently manage the limited resources of the research team and ensure purposeful sampling, the researchers developed categories that they felt represented potentially fruitful areas to explore with relation to the goals of the pilot study. Students who consented to participate in the interviews were placed into one of the four categories, given below:

- high confidence performing content (all ≥ 5) with little time spent outside of class (< 9 hours)
- low confidence performing content (all ≤ 3) with great time spent outside of class (≥ 9 hours)
- high confidence performing content with great time spent outside of class
- low confidence performing content and little time spent outside of class

The cutoff level for confidence was chosen to match the survey design, with items scored 5-7 corresponding to "confident", "very confident", and "extremely confident", respectively. The cutoff for time spent was chosen by the researchers as a conservative estimate of the average time spent by students, wishing to err, if at all, on the side of being too high. Individuals falling in the extremes of each of the categories were given interview priority and contacted first.

The interview consisted of two main parts: a structured set of questions related to general course perceptions and a "think-aloud" portion where students were asked to perform a statics problem while verbalizing their thoughts. The problem chosen (see Figure 2) was a simple 3-dimensional equilibrium problem involving an aircraft wing; all forces acting on the body were directed parallel to one of the given axes. The problem was taken from a textbook different than what the students were using in class and was chosen for its unique subject matter (an aircraft wing) that students had not been exposed to in class. Also, the problem could be solved using minimal math skills, which would tend to focus the problem more towards required statics knowledge. Interviews were conducted toward the end of the semester, and commonly lasted between 20 and 30 minutes. Interviewees were given a $10 gift card as compensation upon completion.

The wing of the jet aircraft is subjected to a thrust of $T = 8$ kN from its engine and the resultant lift force $L = 45$ kN. If the mass of the wing is 2100 kg and the mass center is at G, determine the x, y, z components of the reaction where the wing is fixed to the fuselage at A.

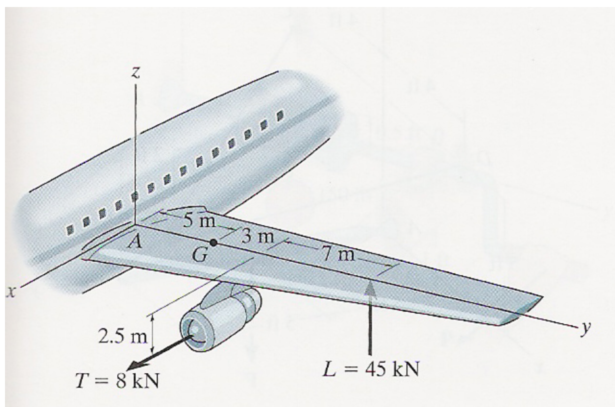

Figure 2. Interview Problem [Taken from Hibbeler, 9].

Survey Results

The survey garnered 191 responses in total; of these, 18 were eliminated from the data set due to age requirements for the informed consent procedure. A brief summary of the results appears below.

		Yes	No	Total
	Enrolled Previously	86 (49.7%)	87 (50.3%)	173 (100%)
	Previously Completed	38 (22 %)	135 (78%)	173 (100%)
		N	Mean	Std. Deviation
Level of Mastery of Prerequisites	Trigonometry	173	5.32	1.05
	Vector Expression	173	4.88	1.10
	Vector Algebra	173	4.95	1.13
Confidence Performing Course Content	Resolving Vectors (2-D)	173	4.52	1.68
	Resolving Vectors (3-D)	171	4.22	1.41
	Creating Equilibrium Eqns. (2-D)	173	4.46	1.71
	Creating Equilibrium Eqns. (3-D)	171	4.23	1.47

Table 1. Survey Summary Data

As can be seen in Table 1 above, nearly half (49.7%) of the respondents had been enrolled in a statics course previously, and over one-fifth (22%) had received a final grade. These high numbers in previous enrollment and completion are likely attributed to the fact that statics is first attempted by most students at this institution during the fall semester; thus, students taking it in the spring are more likely to be repeat students.

Students generally ranked their level of mastery of prerequisite math skills high, with all of the skill means near 5; this corresponds to the "above average" option on the survey. Trigonometry was ranked the highest out of the three, possibly a result of it being taught earlier in high school, whereas vectors are more commonly not introduced until college. Confidence ratings were lower but still between the "neither confident nor unconfident" and "confident" levels (4 and 5, respectively) on the survey. There was a noticeable difference in confidence related to performing 3-dimensional tasks (mean approximately 4.25) compared to 2-dimensional tasks (mean approximately 4.5).

A Mann-Whitney U test was performed to compare the mean responses in confidence for each content area between those who had previously been enrolled in a statics course and those who had not. The non-parametric test was chosen due to the non-normality of the dataset. The results indicated no significant differences at the $p=0.05$ level for any of the content areas (all $p>0.45$). The same test was conducted to compare the mean ratings between those who had completed a statics course and those who had not. Again, no significant differences were found (all $p>0.28$). The results of these tests show that all survey respondents ranked confidence in their abilities to perform each of content areas similarly, regardless of previous formal exposure to statics content.

To investigate whether the students' self-reported levels of prerequisite mastery correlated with their confidences in performing statics content, mean scores of mastery and confidence were calculated for each student. The means were then used to calculate Kendall's tau, a non-parametric measure of correlation. The result shows a significant ($p=0.037$), yet very weak correlation of 0.117 between the two means. Thus, the student's math prerequisite knowledge does not seem to have much of an effect on their confidence performing the selected course skills.

Students also reported spending on average just below 7.25 hours on reading, studying, and working on statics outside of class.

Interview Results

From the pool of 55 students who originally indicated willingness to participate in an interview, 6 were ultimately interviewed. The six students fell into each of the four previously identified categories as shown in Table 2 below (pseudonyms are used in place of actual names):

High Confidence, Great Time Spent	High Confidence, Little Time Spent
Renee	Martin, Caleb, Vanessa
Low Confidence, Great Time Spent	**Low Confidence, Little Time Spent**
Nina, Sam	

Table 2. Interview Participants

Although students with low confidence and little time spent studying were also contacted to participate, they were ultimately not interviewed due to time restrictions; while such cases may be of particular interest to studies such as those on motivation, they were not as relevant to this project's goals.

Student interviews were recorded, transcribed, and then open-coded using a grounded theory approach. This approach was chosen for its flexibility and alignment with the goals of the pilot study; it allowed for the researchers to draw out themes encompassed in the data source that could later be investigated on a larger, more in-depth scale if determined to be worthwhile.

Perhaps the most prominent theme that emerged from the interview data involved the inability of students to break down large problems into smaller steps, perform the smaller steps, and then reconnect them to solve the main problem. In the structured portion of the interview, students commonly identified content that required this sort of thinking as more difficult. For example, both Nina and Martin stated that internal force problems (such as shear and bending moment diagramming) were their most difficult to learn how to solve. These problems typically involve solving equilibrium equations for an entire body before investigating internal equilibrium in several locations in the body, each of which has its own set of smaller steps to go through. Nina summed up the difference that she perceived between these problems and previous material covered in the following statement: "at the beginning of the semester we just did, um bits and pieces, and this one, it's like a bunch of stuff put together. And I keep forgetting some key things I have to remember". Sam and Renee chose multi-body systems (frames and machines) as their most difficult topic; like the beam problems mentioned by Nina and Martin, these types of problems also involve internal forces and require several steps and sub-goals in their solution. These responses seem to indicate that students may view the early course content areas (resolving forces/moments and setting up equilibrium equations) as almost separate entities from the more difficult topics covered later. They could possibly be seen as different types of problems that require different methods of solving them when, in reality, the problems are most basically all variants of the same principle, with the math changing as needed to suit the specific problem goals.

During the workout portion of the interview as well, students struggled with the relatively simple equilibrium problem given to them, again making errors in relating the problem solving process to the overall goal of satisfying equilibrium. Sam, despite having already taken much of the course previously and immediately identifying the problem as a 3-d equilibrium problem, wrote down only one out of the three moment component equations. Once prompted to include the rest, however, he was able to set up the problem successfully. Caleb initially did not include any reaction forces in his free-body diagram, and even when prompted to include them, only labeled force unknowns, remarking that "they did not ask for the moment, they just wanted the reactions at point A and not the moment that the load would be causing". Both Nina and Renee struggled to even begin the problems. Renee commented that she was "not familiar with the exact steps and processes to go through"; when told to instead imagine the airplane wing as a beam, she went through the rest of the problem without difficulty. Even when Nina received a similar prompt, however, she still was unable to determine that moments were needed, saying "I don't think they were looking for that…I guess in the real world you should have all the components, but not in this case". Martin was able to identify the problem type correctly, but also forgot to include reaction forces and moments initially. In all, only one student, Vanessa, could set up the equilibrium equations properly without assistance.

The reason for the differing abilities of each of the students on the workout portion might be attributed to their general approach to learning the course material. Though most students commented that doing problems was a primary key to success, they approached the task differently. Renee, for example, did many problems beyond what was required for homework; this was her third time taking the course, and to her, success meant "just learning how to practice until you get it". She seemed to go through problems as a way of connecting their features to the processes required to solve them. She described the process as follows: "it gets me familiar with the actual pictures and the graphics; I've learned that if I'm not familiar with the graphics then I don't do well on that problem [on the test]." Though she remarked that she was doing well in the course at the time of the interview, her inability to identify the processes required for solving the unfamiliar aircraft wing problem may have been a result of her approach to learning. This approach is common to novices in a field, and many of the other students who were unsuccessful with the interview problem expressed similar approaches to learning how to perform statics problems. Sam and Nina both reiterated the focus by many students to solve problems based on the presentation of a problem. He said that "a lot of students find that they can look at the problem, but if [the answer] is not multiple choice, they don't know exactly what to solve for", while she said of herself, "I just can't see it [unless] it just shows what I have to do in the picture." Vanessa, on the other hand, who not only set up the problem correctly but was able to better verbalize the process that she went through while doing it, spoke of a different approach. Although she also stated that most helpful to her was doing homework problems, she focused on relating theory to each problem. According to her, "if I get the theory inside each one, I can do all of them, so that's what I try to do". Interestingly, this was Vanessa's first time taking the course. It is possible that by making a conscious effort to link each problem to relevant theory, she is indeed building her knowledge around concepts, similar to how individuals with more expertise would. In doing so, she would be able to apply her more generalized knowledge to unfamiliar problems such as the one presented in the interview. Her choice to go beyond the typical structure provided by the course materials and/or instructor shows that she is acting metacognitively and is doing so of her own will.

IMPLICATIONS

The results point to a potential connection between how students study and how that may affect their performance in courses like statics. This has possibly important implications for how statics is taught, namely how to encourage students to build their knowledge around theory and concepts rather than by forming associations between problem features and solution processes. Having good skills in math, which the majority of students reported in the survey, is simply not enough. Caleb summarized the problem nicely: "most of the math once you do it is not that hard, but… I think that's the hardest part is setting the problem up". Getting students to learn these processes effectively might not be properly taught and encouraged in current statics courses. Students who cannot develop the skills necessary to overcome the challenges that this creates on their own, like Vanessa seemed to be able to do, may be doomed to retake the course one or more times before actually learning the material. In fact, upon the conclusion of the semester in which this data was taken, university records indicated that out of the 212 students in this section that completed the course for a grade, 29.2% received a grade of "F" and 30.7% received a grade of "D". Despite the survey results showing nearly half of the respondents had been enrolled in the course before and over one-fifth had previously completed it unsuccessfully, much of the class will be forced to retake the course (possibly again) or change their major. Even out of those who passed, some may still leave the course with knowledge that is not adaptive and cannot be readily applied to new contexts or more advanced theory.

The need for developing better methods to teach statics to large numbers of students seems clear, but future research must determine what these methods involve and how they will be implemented. Modern learning theory should undoubtedly help guide this research. As exemplified by Renee, the behaviorist approach to learning higher level knowledge can be time consuming and potentially limiting. Highly situative approaches have the potential to tackle major issues involving student self-efficacy and motivation, but as mentioned previously, may not be feasible for current institutional structures. A cognitive approach to teaching statics, on the other hand, may be a promising area to explore; still, researchers should remain open to including supportive elements from the behaviorist and situative theories, as their contributions and potential cannot be overlooked.

From the results of this pilot study, several areas of future research in statics education have been identified. Primarily among these is the understanding of how metacognitive abilities can be developed in students taking statics. Some current research indicates that these skills must be developed within the context of individual subject areas [Alexander, 1]; thus, we must look for methods that specifically apply to this course and possibly others in mechanics. Practice with visualization, verbalization, and writing to learn may all be areas that could help students grow metacognitively [Vosniadou, 16]. Another area of future research includes investigating how motivational factors like self-efficacy may be affecting conceptual growth in statics students [Pintrich, 11]. With the reputation of statics as a gatekeeper course plagued by large failure rates, students may enter the course with low self-efficacy despite being confident in their math skills; motivation may also suffer when students are not shown the value of statics to future courses or in practice. These and other areas of research may provide educators with tools to combat current problems.

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