

Using Writing Assignments to Promote Conceptual Knowledge Development in Engineering Statics

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ABSTRACT

Learning of threshold concepts in engineering science courses such as statics has traditionally been a difficult and critical juncture for engineering students. Research and other systematic efforts to improve the teaching of statics in recent years range widely, from development of courseware and assessment tools to experiential and other “hands-on” learning techniques. This dissertation reports the findings from a multi-year, dual-institution study investigating possible links between short writing assignments and conceptual knowledge development in statics courses. The theoretical framework of the study draws on elements from cognitive learning theory – expertise, procedural and conceptual knowledge development, and conceptual change. The way that students approach learning in statics with regard to procedural and conceptual knowledge is explored qualitatively, and the relationship between the writing assignments and conceptual knowledge development is examined using a mixed-methods approach. The results show that students approach learning in statics with varying emphasis placed on procedural and conceptual knowledge development and that a student’s learning approach influences their perception of the written problems and the ways that they utilize them in learning. Thus, they provide evidence that the learning approach of students may be an important factor in the success of interventions designed to improve conceptual knowledge in statics. Increases in conceptual knowledge as a result of completing the written problems are also empirically supported though limited by problems with data collection. Areas for future work in light of these findings are identified.

Dedication

To my family, friends, teachers, and students: thank you for your inspiration, guidance, encouragement, and support.

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I. INTRODUCTION

Statics serves as a foundational course to many engineering disciplines that use Newtonian mechanics to analyze problems. As the name suggests, statics is a branch of mechanics that uses Newton's Laws of Motion to analyze bodies and systems that are in static equilibrium. Steif and Dollár (2005) describe statics, along with dynamics and strength of materials, as the foundation on which much engineering design and practice is based. They also note that many of the core concepts learned in statics, including force manipulation, free body diagrams, and the relationship between internal and external loads, are vital for success in dynamics and strength of materials. As such, statics is a required course for a large portion of engineering majors nationwide. At Virginia Tech, for example, statics is required for eleven¹ out of its fourteen undergraduate engineering degree programs and is a technical elective for the remaining three (Registrar, 2012). For students in these programs, statics is generally taken during the first or second year, just after completing basic courses in the physical and mathematical sciences but before any major exposure to their chosen engineering discipline.

In the engineering community, statics has long been known to be a challenging course for beginning engineering students. Traditionally evidenced by low first-time pass rates and high student attrition, several recent publications from the engineering education community indicate that bad grades are not the only indicators of a problem (Danielson, 2004; Passmore et al., 2010; PS Steif, 2004; P. Steif & J. Dantzler, 2005; PS Steif & Dollár, 2005). In their investigation of student understanding of moments and force couples, Passmore et al. (2010) conclude that students often adopt algorithmic problem solving approaches without demonstrating conceptual reasoning. Danielson (2004) similarly laments that instructors "are often disappointed by our students' lack of understanding of the concepts underlying our instructional materials" (p. 5). These reports among others indicate that many students, even those who pass mechanics courses like statics, may have difficulty conceptualizing the topics that instructors consider essential knowledge for engineering students. That is, despite demonstrating some level of proficiency in using appropriate procedures to solve statics problems, many students lack a deep understanding of the course's core tenets. This learning deficiency can provide complications as students enter courses that build on the statics foundation.

The problem of poor understanding that seems to be facing statics students and educators today is not new, at least not when looking beyond engineering and into the broader educational community. In mathematics education, for

¹ The Chemical Engineering degree program requires a course that combines content from Statics and Strength of Materials.

example, Brownell advocates for the teaching of “meaningful arithmetic” to elementary school children in 1947, about which he remarks:

“Without these meanings to hold skills and ideas together in an intelligible, unified system, pupils in our schools for too long a time have ‘mastered’ skills which they do not understand, which they can only use in situations closely paralleling those of learning, and which they must soon forget.”
(p. 260)

Despite the different context, the sentiments expressed by Brownell might easily be relatable to present-day instructors and engineering education researchers seeking to assist students struggling in statics.

To date, there exist relatively few empirical studies exploring the exact reasons for poor student grades and weak understanding specifically in statics. One may hypothesize that any number of factors, including low student motivation, ineffective instruction, and/or a lack of required background knowledge and skill, among many other factors, may be contributing to the problem. More research is needed to determine other possible causes of poor student understanding as well as to test potential solutions. However, the empirical studies that do exist tend to reach similar conclusions: poor conceptual knowledge is at least partially responsible and better metacognitive skills (particularly self-explanation) among students may lead to improvements (e.g. T. Litzinger et al., 2010; P. S. Steif, Lobue, Kara, & Fay, 2010; Venters & McNair, 2010).

The goal of this dissertation is to help begin the process of bridging research and practice in the field of engineering mechanics education, thus impacting a large portion of existing engineering education curricula. In an effort to help define and solve problems currently facing educators and students in statics, this dissertation synthesizes relevant research originating from a diverse range of fields including the learning sciences, physics and engineering education, and writing and communication. It documents an instructional intervention based on the use of short writing assignments called “process problems” that can be easily integrated into traditional and modern course structures. Finally, it details an empirical study exploring 1) the way that students approach learning in statics with regard to procedural and conceptual knowledge and 2) the effectiveness of the process problems in improving the conceptual and procedural knowledge of statics students who complete them. In all, the artifacts and results provided within contribute to improving the practice of educating more technically competent engineers as well as understanding the role that writing can play in modern engineering education. It is hoped that this dissertation serves

as a stimulus for increased dialogue amongst researchers, educators, and students regarding the problem of poor understanding in statics.

The specific research questions for the study are:

RQ1. How do students approach learning in statics with regard to conceptual and procedural knowledge development? (qual)

RQ2. What is the interaction between the process problems and conceptual knowledge development? (mixed)

RQ2a. How do students utilize the process problems with regard to ways that may work to develop conceptual knowledge, particularly through reflection? (qual)

RQ2ai. Do different learning approaches influence the way that students utilize the process problem assignments? (qual)

RQ2b. To what degree do the process problems affect conceptual knowledge development? (quant)

Chapter 2 provides a summary of relevant literature related to theories about learning (primarily cognitive) that inform much of the discussion related to conceptual and procedural knowledge in mathematics education. I share the same definitions of conceptual and procedural knowledge used by mathematics education researchers, respectively, as “explicit or implicit knowledge of the principles that govern a domain and their interrelations” and “the ability to execute action sequences to solve problems” (Rittle-Johnson, Siegler, & Alibali, 2001). Combining this with research on conceptual change and expertise, I will argue that the lack of conceptual knowledge indicated by others may not only be a problem in itself but also a contributor to the other performance problems associated with the course and that a focus on improving conceptual knowledge may be particularly important. Finally, I will advocate for the use of writing-to-learn methods in statics as one possible way of improving conceptual understanding in statics.

In Chapter 3 I will outline the methods and implementation of the empirical study, which builds on previous work by Hanson and Williams (2008), who used frequent homework writing assignments in a statics course in an effort to improve the self-assessment and writing skills of their students. Their findings point to an increased level of self-assessment (a component of metacognition) due to the writing assignments although they found no differences in learning as measured by course grades. The disparity in their findings may be at least partially explained by considering that traditional tests and homework assignments in statics commonly assess procedural knowledge more so than conceptual knowledge, which may have been improved yet not measured in their study. This study is

similar to Hanson and Williams' original design, yet rather than focusing on improving the writing skills of students, possible improvements in conceptual knowledge are investigated. The intervention from the original study has also been adapted for use on a larger scale within a variety of traditional and modern statics course structures. The use of larger sample sizes, quasi-experimental treatment-control groups, multiple institutional settings, and mixed data sources in this study help to provide more generalizable and transferable results.

Chapter 4 will detail the analysis of data, beginning with interview data collected to answer the first research question and the first two parts of the second research question. Next, results from quantitative data collected to answer the final part of the second research question will be presented.

Chapter 5 will present a discussion of the findings and the contributions that they bring to educators and researchers involved in statics education. Among these contributions is an improved understanding of how students approach learning in statics with regard to the relative importance that they place on conceptual and procedural knowledge, how student approaches to learning may influence the way that they interact with assignments intended to promote conceptual knowledge development through reflection, and how writing assignments may be successfully implemented in large statics courses while providing feedback to students.

II. LITERATURE REVIEW

A. *A Summary of Views on Learning*

Current theories of learning can be divided into three broad views: the behaviorist, cognitive, and situative views, each defining differently what it means to know something, the process of learning and transfer of knowledge into other settings, and how learners are motivated and engaged (J. G. Greeno, A. M. Collins, & L. B. Resnick, 1996). Yet, each view brings its own set of benefits and limitations to the common goal of understanding learning, and one must be careful to “acknowledge the partiality of one’s view rather than confusing it with the way things are.” (Bredo, 2006). Toward this end, each of these three main views will first be summarized, followed by a brief discussion of why the cognitive view was chosen to guide this study.

1) *The Behaviorist View of Learning*

Behaviorist learning theory is the oldest of the three and can trace its roots back to the late 1800s and early 1900s when researchers first began to scientifically study learning. As the name implies, behaviorists generally limit their study of learning to consider only observable behaviors as evidence of knowing (J. D. Bransford, Brown, Cocking, Donovan, & Pellegrino, 2003). For example, classical conditioning theory looks at connections between a particular stimulus and resulting behavioral response. In the famous experiments conducted by Pavlov, dogs that naturally responded by salivating to a food stimulus learned to exhibit the same behavior (salivation) in response to the sound of a bell after many instances of the bell being rung just prior to the presentation of food. Learning according to this theory, then, is the process of strengthening the association between a normally neutral stimulus and a particular behavioral response over many repetitions. In operant conditioning theory, learning occurs as a result of a stimulus (reinforcement or punishment) that is presented after a particular behavior is exhibited. Over time, the reinforcement or punishment respectively strengthens or weakens the association between response-stimulus pair. A great deal of research has been conducted to determine how different reinforcement schedules and techniques like chaining and shaping can be used to intentionally modify behavior (Terry, 2006).

2) *The Cognitive View of Learning*

Cognitive learning theory gained prominence during the “cognitive revolution” that took place around the mid-1900s. In opposition to many behaviorists, cognitivists expand their definition of knowing specifically to consider the internal processes that occur within the mind, which are neither directly observable by a researcher nor necessarily cognizant to a subject. Their experiments, then, must often use indirect evidence to support hypotheses about internal

processes. This has been aided by the incorporation of non-positivist research methodologies and qualitative data sources in addition to the quantitative methodologies traditionally used in scientific research. In more recent years, advances in neuroscience and other fields have allowed for better tools to monitor brain activity and provide more direct evidence of changes in mental states. Regardless, cognitive learning theory continues to provide insight especially into how humans learn and the function of human memory systems (J. D. Bransford et al., 2003). Typical examples of cognitive theories of learning include information-processing theory and constructivism.

Information processing theory hypothesizes about the structure of human memory and how information is stored in the mind. Currently, most information-processing theorists model the human mind as consisting of three different memory stores: the sensory register, short-term (or working) memory, and long-term memory. The sensory register is responsible for taking in raw sensory (auditory, visual, etc.) information and converting some portion of it into a form that can be processed in working memory. While the storage capacity of the sensory register is very large, the information decays very quickly if not sent to working memory. Working memory is where thinking takes place, where information is manipulated, connected to other information, and otherwise utilized. Working memory has a limited capacity and its contents last only for a short duration (about 5-20 seconds) if the information is not actively being used. In contrast, long-term memory is thought to be virtually limitless in capacity and capable of storing information for extended periods of time without being continuously active. When stored information is needed again, it must be retrieved from long-term memory and sent to working memory. Thus, learning in the information processing model consists of successfully taking in information through the sensory register, processing it in working memory, and storing it in long-term memory to be retrieved at a later time. This provides an important distinction between the behaviorist definition of learning and the cognitive definition: even information that has been learned (stored in long-term memory) may not translate into observable behavior in some situations due to retrieval failure (Ormrod, 2009).

Constructivism is another important theory in the cognitive view of learning. A primary tenet of constructivism is that new knowledge is built around and linked to pre-existing, or prior, knowledge. Learning is a process by which learners attempt to connect new facts, ideas, or information to those already learned from previous experiences. An important implication of this is that each individual may construct unique knowledge structures (and thus have a unique learning experience) even when presented the same source of information (Ormrod, 2009).

Principles from constructivism and information-processing theory are often combined in cognitive research to yield further insight into knowledge development and usage. When information is connected to relevant prior knowledge, for example, it is learned (stored) more easily and is more likely to be remembered (retrieved from long-term memory) when needed. This type of learning is often called meaningful, or deep, learning. In contrast, rote learning, which is commonly accomplished through memorization and rehearsal, often results in more time spent learning and more difficulty recalling information from long-term memory. Missing or incomplete prior knowledge may also make it difficult to store new information effectively and may encourage rote learning. Beyond being easier to store and recall, well-connected pieces of information about a common topic have another added benefit in that they can be mentally grouped to form a concept, which can be processed in working memory as a single chunk, freeing up cognitive resources. This so called conceptual knowledge is believed to be one of the hallmarks of expertise (J. D. Bransford et al., 2003). Connections made with prior knowledge are not always helpful, however; incorrect prior knowledge may result in knowledge connections that are flawed, creating misconceptions (Ormrod, 2009).

3) *The Situative View of Learning*

Situated learning theory highlights a relatively recent departure by some cognitivists from the focus of an individual's mind as the locus of knowledge creation and storage. Instead, situativists argue that knowledge is created and distributed among groups of people, objects, and activities and subject to particular contexts, social norms, and other environmental factors (J. Greeno, A. Collins, & L. Resnick, 1996). For example, in the theory of legitimate peripheral participation, learning is a process by which individuals become increasingly able to participate in the authentic activities of a community of practice as they gain experience (Lave & Wenger, 1991). Brown et al. discuss the implications of situated learning in school settings, where they argue that school culture undoubtedly influences knowledge development and may restrict the transfer of knowledge learned in school settings into different contexts (J. Brown, Collins, & Duguid, 1989).

4) *Which Theory to Use?*

A growing view among scholars is that elements from each theory can play an important role in our understanding of human learning. Greeno, et al. describe the different views as “fram[ing] theoretical and practical issues in distinctive and complementary ways, somewhat in the way that physics, chemistry, and biology frame issues surrounding processes such as genetic replication in different but complementary ways (1996, p. 16).” This

perspective has important implications for both educational research and practice. Educators should be open to considering instructional tools and methods supported by findings from multiple research perspectives. Researchers also should remain open to considering the contributions from alternative views of learning in explaining the phenomena they are studying since each could support a theoretical framework that would result in different interpretations of the data collected. For this reason, it is important to establish and communicate the theoretical framework chosen by the researcher to guide each study.

On one hand, evidence of and potential explanations for improved learning as a result of the process problems used in this study could be productively viewed through the situative perspective. To complete the process problems, students are directed to describe their solution process as they would to another student. Applying the cognitive apprenticeship model to view a student's progression from embedded activity to generalization (J. Brown et al., 1989) in this context could correspond to modeling and/or coaching performed by the instructor in the classroom, followed by collaboration and multiple practice through traditional homework assignments, and finally, reflection and articulation via the process problems. Drawing from the theory of legitimate peripheral participation, the process problems might provide a greater ability to participate in the practices of the engineering community by building the skills necessary to articulate a solution procedure in words similar to the way that more advanced members (presumably) can.

On the other hand, viewed through the cognitive perspective, potential learning gains due to the process problems might be attributed to students translating one from symbol system (mathematics) to another (writing) and identifying of gaps and inconsistencies in existing conceptual knowledge through reflection. Constructivists in particular might view a student's prior knowledge as developing from some initial state and either being altered and/or increased through practice and subsequent reflection. From the information processing view, encoding the same information in long term memory using more than one symbol system and making conceptual connections between symbol systems may facilitate retrieval and lessen cognitive demands when problem solving.

Thus, even when given the same instructional intervention, either perspective might rightfully be used to guide this study, albeit with different suggestions as for what evidence might constitute learning. However, from a practical standpoint, it is this author's view that at the present time, the cognitive perspective provides the most readily available way to accomplish the goals of this study. For one, most students in modern formal education settings are

still assessed based on their individual knowledge and abilities. Since one goal of this study is to evaluate an instructional intervention that can be easily implemented (and assessed) within current course structures, it should utilize assessments that are ready to use and easy to implement. Many of the existing tools used to evaluate changes in conceptual knowledge such as concept inventories and recent research involving procedural and conceptual knowledge development are cognitive in nature and tend to focus on the individual rather than considering the interactions amongst individuals and various elements of their surroundings. For these reasons, the cognitive perspective seems to be a good choice to guide this study. Relevant findings from related research will be reviewed in more depth in the following sections. One would 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.

B. Key Research Related to Cognitive Learning Theory

The theoretical framework that will be used for this study, represented visually in Figure 1 below, draws mainly upon three major bodies of research informed by the cognitive perspective of learning: expertise and the differences between novices and experts; the development of procedural and conceptual knowledge; and conceptual change and misconception identification and correction.

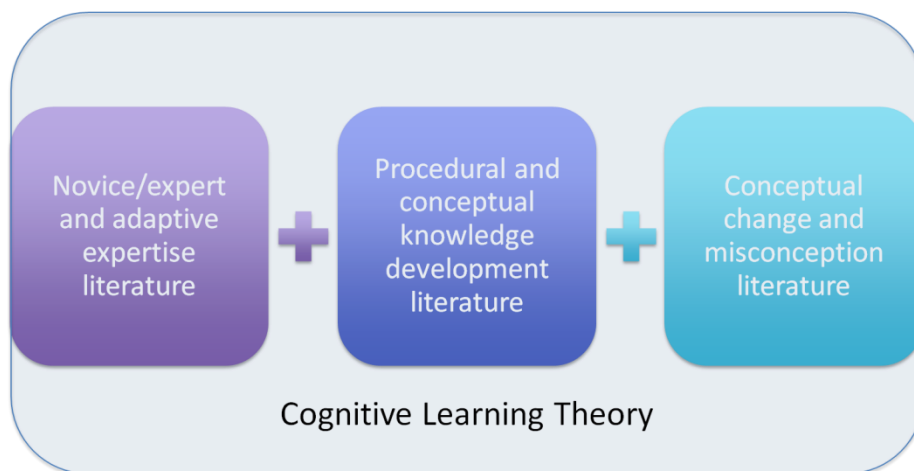


Fig. 1. Theoretical Framework.

These three areas, though all influenced by cognitive learning theory, have been largely (though certainly not solely) developed by researchers from different communities: cognitive science, mathematics education, and physics education, respectively. Yet, it is the belief of this author that these three areas are linked together in fundamental and important ways despite the unique contexts in which they were originally studied. Furthermore, the consideration of

these areas together may have important implications for engineering science courses like statics. Each of these areas will be reviewed below, followed by a synthesis of their relevance to statics.

1) Differences Between Novices and Experts

Regardless of learning theory used, a common goal of formal instruction is the growth and development of student knowledge, guiding students from a novice level of understanding towards that of an expert, someone proficient in the practice of a domain. Gaining expertise is a time-consuming process involving a great deal of effort and practice, so while it is unrealistic to expect college students to reach the level of expert in their field by the time they graduate, instruction should attempt to place students on a trajectory toward this goal (T. A. Litzinger et al., 2011).

For cognitivists in particular, an expert is someone with considerable domain knowledge that is highly structured around key concepts (Alexander & Winne, 2006). From the constructivist and information-processing views discussed previously, this means that experts have more than simply a large quantity of knowledge; their knowledge is also rich in meaningful connections and organized into large related chunks, or concepts. Thus, they possess high levels of quality conceptual knowledge, knowledge about interconnected pieces of information and how they relate to each other. Their well-developed knowledge structure facilitates quick retrieval of pertinent information from long-term memory and allows them to process the information in working memory more efficiently (J. Bransford, Brown, & Cocking, 2003). In contrast, knowledge possessed by novices tends to be considerably less developed although there is disagreement about what the exact structure of this undeveloped knowledge typically looks like. Some researchers contend that novice knowledge is coherent and “theory-like” (Carey, 1999; Gopnik & Wellman, 1994), suggesting that connections may be present though possibly incorrect, incomplete, or connecting unrelated pieces of information. Others believe novice knowledge to be highly fragmented, still in pieces with relatively few connections (DiSessa, 1988). These opposing views would suggest possibly important differences in the methods of instruction best able to improve conceptual knowledge development in novices (DiSessa, Gillespie, & Esterly, 2004). This idea will be elaborated on more in the conceptual change summary.

In addition to conceptual knowledge, experts also possess a large amount of procedural knowledge, knowledge about how to do things, gained from their years of practice and experience. In fact, many experts have performed procedures that are common in their field so often that they reach a level of automaticity in which they can perform the task quickly with little cognitive effort (Ormrod, 2009). An expert’s highly developed procedural knowledge thus

affords him improved performance and, in the case of domains like mechanics, better problem solving abilities when compared to novices, who may struggle when needing to devote significant cognitive resources to perform the same task. However, just like conceptual knowledge, procedural knowledge can vary in quality. Routine experts, those who hone specific abilities and thus have a large amount of procedural knowledge, are skillful in performing familiar tasks quickly. Adaptive experts, in contrast, can use their knowledge flexibly and innovatively in contexts beyond those in which they were originally practiced (Alexander & Winne, 2006). As opposed to routine experts, adaptive experts may understand why certain procedures work and may modify or create new procedures or search outside of their specific domain for better solutions to unfamiliar problems (Hatano & Oura, 2003).

2) Procedural and Conceptual Knowledge Development

As noted above, expertise is dependent on the quantity and quality of both conceptual and procedural knowledge. Yet it is not clear as to which type of knowledge develops first in novices and hence which should be emphasized in instruction. Dialogue regarding the primacy and relative importance of conceptual and procedural knowledge in learning has been underway for some time, particularly in the context of mathematics education. Both theoretical arguments and empirical findings have been used to advance positions supporting a procedures-first or concepts-first approach to instruction (see Rittle-Johnson, Siegler, & Wagner Alibali, 2001 for a review). However, there has not been widespread consensus supporting any position, and the result has been an ongoing debate dubbed the “math wars” (Star, 2005) (e.g. (Baroody, Feil, & Johnson, 2007; Byrnes, 1992; Engelbrecht, Bergsten, & Kagesten, 2009; Hiebert, 1986; Rittle-Johnson & Alibali, 1999; Sfard, 1991)). Rather than advocating solely for conceptual or procedural knowledge as the basis for the other, some researchers have more recently embraced a less competitive view. For example, in 2001, Rittle-Johnson and Alibali (2001) offered their view of the two types of knowledge as located on different ends of a continuum and not always separable. In this model, either procedural or conceptual knowledge may be learned first, after which the other type is often learned as well. Thus, they suggest that the two types of knowledge are interlocked and must develop together for effective learning. Yet while the exact interplay between procedural and conceptual knowledge is not yet fully understood, most researchers agree that the two are at least in some sense different, yet both required, for meaningful learning.

In the opening chapter of Heibert’s seminal book, he and Lefevre provide an overview of the theoretical relationships between conceptual and procedural knowledge in mathematics. They contend that possessing conceptual knowledge enhances procedural knowledge by developing meaning for symbols, being able to better recall

and utilize appropriate procedures, and promoting transfer to similar problem types. Similarly, possessing procedural knowledge enhances conceptual knowledge by using symbols to represent and develop concepts, grounding concepts through applications to problem solving, and prompting the need for development of new or revised concepts. Yet, they also acknowledge that these intended benefits of possessing both knowledge types are not always realized in practice. (Hiebert & Lefevre, 1986)

It seems reasonable that the arguments made for the relationship between procedural and conceptual knowledge in mathematics can be extended to help characterize the problems facing students in engineering mechanics. As mentioned in Chapter 1, the development of conceptual knowledge in statics seems to be particularly troublesome for students despite their ability to sometimes still carry out correct procedures when solving problems. Yet, procedural and conceptual knowledge each support the development of the other, meaning that a lack of conceptual knowledge in statics is not only a problem itself, but it may also be a cause for problems involving deficiencies in procedural knowledge. According to Heibert and Leferve:

The problem with learning procedures without concepts is that the procedures become likely victims of all of the maladies identified earlier. Procedures that lack connections with conceptual knowledge may deteriorate quickly and are not reconstructable; they may be only partially remembered and combined with other subprocedures in inappropriate ways; they often are bound to the specific context in which they were learned and do not transfer easily to new situations; and they can be applied inappropriately without the benefit of a validating critic to check the reasonableness of the outcome. Hence, although routinized procedural skills are essential for efficient problem solving, related conceptual knowledge is needed to give procedures stability and effectiveness. [emphasis added] (Hiebert & Lefevre, 1986)

Thus, conceptual knowledge development is an essential component of learning in statics, where procedures form a large portion of what is taught and assessed.

3) Conceptual Change and Misconceptions

As novices transition from naïve understandings to more robust conceptions, their conceptual knowledge is altered through a process called conceptual change. This change may be in the form of enrichment, in which new conceptual knowledge is added to existing knowledge structures, or it may be in the form of revision, in which the structure of

existing conceptual knowledge is altered (Vosniadou, 1994). However, as mentioned previously, the exact mechanisms involved in conceptual change as well as how instruction can best promote it depend on the existing conceptual structure of knowledge in novices, for which a wide range of views exist (e.g. Chi, Slotta, & De Leeuw, 1994; DiSessa et al., 2004; Vosniadou, 1994). Revision would obviously be a more important instructional goal if novice knowledge were already highly connected and “theory-like”. Conversely, novice knowledge that is largely unconnected and/or not present at the beginning of instruction would require a focus on enrichment.

A good deal of previous research in science, primarily physics, has been focused on identifying and correcting common misconceptions, which Vosniadou (1994) views as “student’s attempts to interpret scientific information within an existing framework theory that contains information contradictory to the scientific view” (p.46). This definition would imply that the presence of a misconception indicates prior knowledge that is “theory-like” and would require conceptual change in the form of revision. If misconceptions that students possess upon entering the classroom are not addressed, they can make learning and applying concepts from a course particularly difficult and may inhibit revision during the learning process. For example, in regard to engineering mechanics, common misconceptions related to various aspects of force have been reported, including its direct relationship to acceleration (rather than velocity), the two-body nature of forces, and determination of the forces acting on a particular body or group of bodies when drawing free-body diagrams (R. Streveler, Litzinger, Miller, & Steif, 2008). These misconceptions would support the development of instruction designed to promote conceptual change through revision.

Identifying misconceptions that students possess on a large scale among many disciplinary areas has been attempted through the development of concept inventories, sets of questions designed to assess one’s level of understanding of a particular concept or group of concepts; the inventories are usually designed and evaluated to establish validity and reliability of the results. The first and most widely recognized concept inventory is the Force Concept Inventory (FCI) published in 1992 (Hestenes, Wells, & Swackhamer, 1992) for Physics. According to its creators, the test measures student understanding of the concept of Newtonian force along 6 different “dimensions”, which together form a complete understanding of the concept. The inventory presents students with multiple choice questions that, in addition to a correct answer, contain incorrect answer choices based on common misconceptions that many people logically form based on casual observation of everyday objects. The FCI has been given to tens of thousands of students across the country, has been analyzed by dozens of researchers, and still remains an important

tool in the physics education community. As a result of its widespread influence, many other fields of science and engineering have begun to develop and use their own concept inventories for their respective disciplines using the FCI as a model (e.g. Martin, Mitchell, & Newell, 2003; Midkiff, Litzinger, & Evans, 2001; P. Steif & J. Dantzler, 2005; R. A. Streveler, Miller, Santiago-Roman, & Nelson, 2011).

Despite the creation of many concept inventories inspired by the FCI, the specific ways that authors craft their own inventories is rather diverse. Lindell et al. (2007) investigate the processes and methods used by various researchers to develop 12 different concept inventories in the physics and astronomy fields among those with published methodologies, including the FCI. Their analysis highlights differences in what is reported by authors of the various inventories, including significantly different ways of formulating topics and questions as well as establishing reliability and validity. Lindell et al. suggest that efforts be made to standardize the ways that concept inventories are developed and documented for review using common steps followed in instrument design literature (they give Crocker and Algina, 1986 as a reference). Like concept inventories in physics and astronomy, those in the rest of the sciences and engineering also are created using a variety of methods and may benefit from a more uniform approach.

A Statics Concept Inventory (SCI, or more recently named the Concept Assessment Tool for Statics, or CATS) was published in 2005; it consists of 27 multiple choice questions grouped into five categories: free-body diagrams, static equivalence, forces at connections, friction limit, and equilibrium (P. Steif & J. Dantzler, 2005). Measures of validity and reliability of the SCI have been reported, and it is a widely used instrument in engineering education research involving statics.

On a smaller scale, researchers and instructors are trying to assess students' conceptual and procedural knowledge using methods including problem-sorting tasks similar to those conducted by Chi et al. (1981) and oral interviews consisting of think-aloud protocols, in which individuals are prompted to articulate their thoughts as they perform a task such as solving a problem (Ericsson & Simon, 1992). These methods are argued to give better insight into the problem-solving processes and structure of student knowledge than concept inventories can deliver (Smith & Tanner, 2010). Still, concept inventories currently remain widely used in practice as a tool to probe students' misconceptions of a particular concept or group of concepts.

To complicate matters further, many concepts related to engineering are believed to be difficult to teach even in the absence of preexisting misconceptions. Termed threshold concepts, they are said to be an integral part of a discipline that transform ways of thinking and provide a “portal” into higher levels of understanding (J. Meyer & Land, 2003). Streveler et al. (2008) summarize research that shows that many engineering concepts such as force, heat, light, and current are possibly difficult to grasp because they involve “emergent phenomena”, which occur indirectly as a result of underlying physical principles that cannot be directly observed. Thus, emergence may be a threshold concept that is required for better understanding of force, heat, light, and current. Threshold concepts like emergence may point to a need for instruction that focuses on knowledge enrichment rather than revision.

4) Synthesis of Cognitive Learning Theory Framework

The three research threads discussed above, although originating from different communities and situated in different disciplinary contexts, all help to frame the problems that are currently facing students and educators in engineering mechanics. Considered together, they make a strong argument for the goal of improved conceptual knowledge development in statics and offer guidance as to how best to achieve, and monitor students’ progress towards, that goal.

Studies on the differences between novices and experts highlight that the combination of quality conceptual and procedural knowledge allows experts to store, recall, and utilize relevant knowledge more efficiently. Extensive prior knowledge also allows experts to more easily identify relevant features of problems they are solving; novices, on the other hand, tend to base their solution process on possibly irrelevant surface features of problems (Chi et al., 1981; deGroot, 2008). Thus, both types of knowledge should be emphasized in formal education settings.

Findings from mathematics education reaffirm the importance of procedural and conceptual knowledge, but also go further to suggest that the two enrich each other and must be developed together. In statics, inadequate conceptual knowledge among students who pass has itself been identified as a problem, but it may also be cause of underdeveloped procedural knowledge, which might explain the poor performance among those who struggle and/or are unsuccessful. In this way, the sentiments expressed in the following quote about arithmetic courses in elementary education might also apply to many college-level statics courses:

The separation [of students’ conceptual and procedural knowledge], together with the emphases of ordinary instruction programs, seems to lead to an overreliance in procedural skill and on syntactic

features of the written symbol system. The result is that students' mathematical behavior often consists of looking at surface features of problems and recalling and applying memorized symbol manipulation rules. Mathematically unreasonable answers are often produced, and performance is low across a range of problems, even on those directly instructed and frequently practiced. (Hiebert & Wearne, 1986, pp. 199-200)

Indeed, this seems to reiterate the same findings from the previously cited study of novice problem solving in physics conducted by Chi and colleagues (1981). Similar to math and physics, traditionally common methods of statics instruction like working out problems may direct students to focus on developing procedural knowledge. This may not be the intention of the instructor, who would presumably be explaining their use of procedures and highlighting relevant conceptual knowledge as they work through a problem solution. However, studies of experts reveal that although their highly developed knowledge makes problem solving easier for them, it can also make them less skilled at making evident to learners their thought processes along the way (Alexander & Winne, 2006). This "expert blind spot" may put instructors at a disadvantage when demonstrating problem solving in front of a class.

Considered together, the observations made by statics educators, the research findings from mathematics and physics education, and studies on expertise all point to a need for improved conceptual knowledge development among statics students. Yet, studies on conceptual change make it clear that this process is not always easy nor well understood. The structure of the prior knowledge of incoming statics students, whether theory-like or fragmented, would determine whether instruction should focus on revision or enrichment, respectively. Streveler et al. (2008) point out in their review that research investigating what novice to expert transition looks like and how knowledge structures change during transition (conceptual change) has not yet been conducted specifically for engineering subjects like statics. However, they discuss that misconceptions related to force are common and that threshold concepts like emergence may first need to be learned even in the absence of misconceptions, possibly indicating a need for statics instruction to accomplish both revision and enrichment.

Though concept inventories were originally developed to detect misconceptions that student possess so that they could be revised through instruction, they also provide one possible way of assessing on a large scale the effect of instruction in promoting conceptual change by giving a snapshot of student misunderstandings at the beginning and end of a course. If revision has occurred, then the average score on the concept inventory should rise indicating a

lower number of persisting misconceptions. However, recent studies using the SCI indicate that student scores are consistently low and amount to random guessing when taken as a pretest, which may mean that incoming students do not have misconceptions upon entering the course so much as no connections and/or no relevant declarative knowledge related to statics (P.S. Steif & Dollar, 2012). This would further reinforce the need for instruction that promotes enrichment.

C. Writing and Learning

In light of the challenges presented by conceptual change, it is proposed here that writing may be a useful tool in teaching and learning conceptual knowledge. As with the think-aloud method, writing may be a way for instructors to “see” and understand a student’s thought process and identify any incorrect assumptions or analogies that the student makes when explaining concepts, providing a starting point for revision through instruction. For students, it may also be a way to make connections among relevant pieces of knowledge, assisting in conceptual knowledge development through enrichment. Writing may also be used to prompt students to reflect on their own thought processes when solving problems, which may promote revision of incorrect and/or inconsistent knowledge. The ways that writing may be used to accomplish these goals along with the research supporting these processes is summarized below.

Writing as a means of learning is not a new idea in formal education settings. Klein (1999) mentions two time periods in which the notion of including writing across the school curriculum has been popular, first in the 1930s-50s and more recently beginning in the 1970s. Following Janet Emig’s (1977) classical argument for the explicit connection between writing and learning, many teachers in the 80s and 90s began incorporating writing into their classrooms. During this time, two major movements emerged, arguably with somewhat different views regarding writing in the classroom: Writing Across the Curriculum (WAC) and Writing in the Disciplines (WID) (Ochsner & Fowler, 2004).

Writing Across the Curriculum is the older of the two writing movements; it is also the one traditionally associated with supporters of the writing-to-learn (WTL) approach. WAC proponents argue for the use of writing assignments as a way to improve content learning among students in a wide range of courses including mathematics, history, science, and others. Most of the learning theory supporting their approach comes from cognitive views of psychology, specifically information-processing models of memory, the conceptual structure of long term memory, and metacognition (Bangert-Drowns, Hurley, & Wilkinson, 2004; Emig, 1977).

Despite the strong theoretical ties made between cognitive learning theory and WTL approaches, there has been little in the way of empirical research evidence to strongly support these claims. Klein (1999, p. 252) notes this in his review, where he describes four cognitive hypotheses common in WTL literature, but concludes that only one had received more than “modest to indirect” empirical evidence specifically linking learning to writing. Bangert-Drowns, et al. later conducted a meta-analysis of writing-to-learn studies to search for common factors that showed evidence of promoting learning through writing assignments. From analyzing the reported results from 48 treatment-control studies representing a wide range of treatment designs, student grade levels, and subject areas among other variables, they concluded that WTL interventions had a generally positive, yet small effect on measures of traditional academic performance. Moreover, they found some evidence that shorter writing assignments and metacognitive prompts each showed a relatively strong positive correlation with effect size (Bangert-Drowns et al., 2004). Still, both reviews highlight that WTL research can benefit from more experimental evidence that specifically links writing processes to improved learning.

Writing in the Disciplines is the second major writing movement that arose in the early 1990s. Started by many who questioned the quality of the findings linking writing to learning (e.g. Ackerman, 1993), this group advocates instead for exposing students to the specific ways that writing is used by experienced practitioners in their area of study, thus learning about the discipline itself. WID supporters believe that through participation in the actual work of the discipline, students become accustomed to the norms of that discipline, including common modes of discourse and what types of knowledge are valued. Thus, the movement has been nicknamed the learning-to-write movement, in part to highlight the difference in their approach from the WAC group. Theoretical backing for WID usually comes from situated views of learning, specifically the ideas of socially-mediated knowledge, apprenticeship models of learning, and legitimate peripheral participation (Carter, Ferzli, & Wiebe, 2007; Poe, Lerner, & Craig, 2010, pp. 1-18).

Still, Carter et al. argue that WID supporters risk falling prey to the same criticisms levied against the WAC movement should researchers not begin to investigate how learning to write in a discipline results in improved learning about that discipline. They suggest, as Ackerman did of WTL research, that qualitative research methods may play an important role in articulating some of the ways in which this learning occurs (Carter et al., 2007).

The body of literature supporting both of the writing to learn movements shows that writing has promise as way of increasing learning in students. From the cognitive perspective, writing can be seen as a tool for linking relevant pieces of related information, developing the organizational structure of information in long-term memory. Through reflection, it can also help learners become more metacognitive and self-regulating, better able to identify gaps both in their knowledge and in the way that they approach learning. From a situative perspective, it can introduce learners to the terms used by professionals and the way that discourse in the field is structured. This in turn may help cognitive growth by providing better accessibility to texts, lectures, and other sources of information that are commonly written and shared by more experienced participants in the field. Interventions in engineering using these ideas are already being implemented (Artemeva, Logie, & St-Martin, 1999; Kalman, 2011).

Critical also, though, is the collection of experimental evidence that offers support to the claims of why and how writing may promote learning. This may best be accomplished through a combination of quantitative and qualitative data sources in which writing can serve both as an intervention and a source of data. For example, writing may be analyzed to make evident the organizational structure of information in student's minds and how that may change over the course of an intervention or to establish the ways that students construct arguments and support their claims as an indication of their socialization into the discipline. Thus, writing may be particularly important for introductory courses in which students are simultaneously negotiating the learning of course content, the development of strong study habits that promote deep learning, and becoming socialized into the unfamiliar modes of discourse valued by that discipline.

D. Summary

Conceptual and procedural knowledge development in novices is an essential component of progress toward expertise. Deficiencies in conceptual knowledge not only result in poor understanding of course content, but may also inhibit the development of more advanced procedural knowledge that supports successful problem solving like that shown by adaptive experts. The extra flexibility demonstrated by adaptive experts may occur as a result of metacognition, the ability to monitor one's own understanding and take appropriate steps to improve one's learning (J. D. Bransford et al., 2003). Metacognition is closely related to self-regulation in which learners "make decisions about, direct, monitor, and evaluate their own learning and behavior" (Ormrod, 2009, p. 105). Though metacognitive skills can be taught, it is believed that they must be done so within the context of a particular domain to be effective (J. D. Bransford et al., 2003). Guiding statics students through a metacognitive process might encourage them to

identify deficiencies in their understanding, which may prompt them to seek out sources that would allow for revision or enrichment to correct the deficiency.

In statics, students may be focusing on developing procedural knowledge without accompanying conceptual knowledge. Writing-to-learn methods might provide an effective way of having statics students build conceptual knowledge related to statics through reflection, a key component of metacognition. In particular, the process problems used in this study encourage students to reflect on their existing procedural knowledge as a starting point for the development of related conceptual knowledge. This may provide a mechanism for linking procedures and concepts in long-term memory, which would facilitate retrieval and reduce cognitive load during problem solving.

III. METHODS

The primary goal of this study was to investigate possible changes in students' conceptual and procedural knowledge of statics content as a result of completing a series of required homework writing assignments (hereafter referred to as process problems). Another goal was to investigate the learning approaches of statics students with regard to conceptual and procedural knowledge development. The resulting research questions are presented below:

- RQ1. How do students approach learning in statics with regard to conceptual and procedural knowledge development? (qual)
- RQ2. What is the interaction between the process problems and conceptual knowledge development? (mixed at the discussion level)
 - RQ2a. How do students utilize the process problems with regard to ways that may work to develop conceptual knowledge, particularly through reflection? (qual)
 - RQ2ai. Do different learning approaches influence the way that students utilize the process problem assignments? (qual)
 - RQ2b. Do the process problems affect conceptual knowledge development? (quant)

The selection of the research methods needed to best answer these questions was directly influenced by my worldview, which I would describe to be largely pragmatic. Pragmatists reject the incompatibility of post-positivist and constructivist methodologies and argue that the research questions, not the worldview of the researcher, should be the deciding factor in choosing methods. Pragmatism even supports the mixing of methodologies within a single study, arguing that the mixing can provide a more complete explanation than either previous methodology could alone (Tashakkori & Teddlie, 1998, pp. 3-30). Toward this end, I chose a mixed-methods approach to data collection and analysis, which “can unite the primary advantages of [quantitative and qualitative research]—namely breadth and depth”, respectively (Leydens, Moskal, & Pavelich, 2004, p. 69). While further work remains on developing a unified glossary of mixed-methods terms and design typologies that are widely agreed upon by scholars (Tashakkori & Teddlie, 2003, pp. 680-691), I chose to adopt the framework provided by Creswell and Plano Clark, who define a mixed methods study as one that “...focuses on collecting, analyzing, and mixing both quantitative and qualitative data in a single study or series of studies” (2007, p. 5). In the same work, Creswell and Plano Clark also outline and discuss a few basic mixed method design typologies differing in timing (when the data are collected relative to each other), priority (which data serves as the primary means of analysis), and mixing (when in the research process is the

data brought together). The Creswell framework is common among scholars in leading engineering education journals (e.g. Borrego, Douglas, & Amelink, 2009), and it was used as a guide in constructing this study’s research design.

The research design for this study featured simultaneous collection of qualitative and quantitative data during each implementation. The intervention was implemented a total of four times over the course of three terms at three different institutions as indicated in the project timeline found in Table 1 below. For each implementation, analysis of the quantitative and qualitative data was conducted independently before being mixed. This chapter details the settings and participants involved in each implementation of the intervention, the collection and analysis of the data, considerations made to ensure rigor and trustworthiness, and methodological limitations.

TABLE 1. PROJECT TIMELINE.

Term	Institution(s)
Spring 2011 (Pilot)	Large Mid-Atlantic Public Institution
Fall 2011	Large Mid-Atlantic Public Institution Large Southeastern Public Institution
Spring 2012	Small Mid-western Private Institution

A. Ethical Considerations

The research study procedures presented here were approved, as required, by the Institutional Review Board (IRB) for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and were carried out under its supervision. While Virginia Tech’s IRB was the primary office charged with the protection of all of the participants involved in this study, approval was also sought out and obtained at the local IRB offices of the participating partner institutions when possible.

B. The Process Problem Assignment (The Intervention)

The “process problems” used in this study were a close adaptation of the “explain-a-problem” assignment created by Hanson and Williams for their original study (2008). As the assignment names suggest, students completing a process problem were to explain, using only words, the process that they used to solve a particular homework problem—that is, they were asked to translate their mathematical solution processes and any figure construction processes into words. Though the basic assignment itself did not change over the course of this study, the supporting materials given to the students and used by the graders did change as result of feedback from the pilot study; these supporting documents and the changes that were made are outlined below.

1) The Pilot Implementation (Spring 2011)

The process problem guidelines sheet given to the students participating during the pilot can be found in Appendix A1. This sheet outlines the assignment objectives, instructions for completing the problems, and a listing of the assignment's four grading criteria. Students were also given a worked-out statics problem and a corresponding process problem solution as an example (Appendix A2). The process problems turned in by students during the pilot were assigned a numeric score based on the grading rubric found in Appendix A3, which was not shared with students during the pilot. The guidelines and rubric closely resembled those created by Hanson and Williams, with minor modifications made during norming sessions conducted with the two teaching assistants who were responsible for grading the process problems during the pilot. In accordance with the rubric, students were given either full credit, partial credit, or no credit based on the level of satisfaction of each of the aforementioned four grading criteria. In the event that a student's work contained elements belonging to more than one grading level within a particular criterion, the student was given the score of the lower level. For example, a process problem that described a fundamentally sound approach but contained one equation described algebraically would receive partial credit for the second criterion, "Has the student demonstrated an understanding...?".

2) Subsequent Implementations (Fall 2011 and later)

Based on feedback from students participating in the pilot study, the guidelines were revised as shown in Appendix A4 in an effort to more explicitly link the grading criteria with the assignment instructions, which some students reported as being unclear. In addition, feedback from the pilot graders supported the decision to add a new criterion on the updated grading rubric (Appendix A5) solely addressing formatting requirements. This change moved the page length requirement out of the third criterion, "Is the description written such that an expert can understand...?", and combined it with two other formatting requirements that were not explicitly listed on the pilot rubric yet were listed in the instructions to the students. The updated rubric was shared with students at the beginning of the course along with the rest of the supporting materials. The new guidelines and rubric were unchanged throughout the remainder of the study, and students were given the same example problem shown in Appendix A2 for each implementation.

C. Participants and Settings

This study took place over the course of three semesters at three different institutions as indicated in the project timeline provided in Table 1. The different institutions were chosen to provide varied contexts in an effort to increase

the generalizability and transferability of the findings to a broader range of settings (i.e., large and small, public and private). Large institutions were more heavily targeted since the process problems were originally developed for use in a small institutional setting and it was desired to demonstrate that they could be effectively scaled to larger settings. The following subsections will characterize the research subjects (participants) involved during each implementation and give descriptive information about the implementation at each setting.

1) Spring 2011 (Pilot) at Large Mid-Atlantic Public (LMAP) Institution

The pilot study took place at a large public research university located in the mid-Atlantic region of the United States. The LMAP institution offers a wide range of degree programs at the undergraduate and graduate levels. Its engineering college has the largest portion of undergraduate enrollment at the university, nearly twice the number of students as the next largest college. Statics at this institution is offered to all engineering majors through a single department. An academic year comprises two semesters, and students commonly take statics during the first semester (fall) of their second year; thus, the spring offering of the course is more likely to be composed of a larger number of advanced first year students, transfer students, and students who are retaking the course.

In total, all three sections of statics offered in spring 2011 at LMAP, each with a maximum capacity of 155 students, took part in the pilot study. Two of the sections were used to set up a quasi-experimental design in which one section (hereafter referred to as EX1) received the process problem intervention while the other (hereafter referred to as C1) was used as a control. EX1 and C1 were taught by the same instructor, an associate professor who had been teaching the course for many years. The two sections were taught back-to-back twice per week for an hour and fifteen minutes per class in a traditional lecture-style format. They shared the same lecture content, four tests, a comprehensive final exam, and homework assignments consisting of approximately six problems collected twice per week via an online system that accompanied the course text. In addition to the common homework problems, section EX1 was asked to complete thirteen process problems over the span of the course at a rate of approximately one per week. The students in EX1 wrote process problems only for homework problems that they were required to complete already in an effort to keep homework time requirements between the two sections comparable; the instructor did not wish to reduce the number of normal homework problems for EX1 to compensate for the process problems. The remaining section that participated in the pilot, section EX2, was taught by a different instructor and thus had different lectures, homework assignments, tests, and exam questions than sections EX1 and C1. The instructor for EX2 was a graduate student. However, section EX2 completed the same process problems as section EX1. Students in sections

EX1 and EX2 typed the process problems and turned in hard copies during class meetings. It was left up to the discretion of the instructor how much the process problems would contribute to the 15% of the overall course grade reserved for homework. The instructor for EX1 ultimately counted the problems for 5% of the course grade while the instructor for EX2 counted them for approximately 4.25% of the course grade.

The process problems for sections EX1 and EX2 were graded by two graduate teaching assistants (TAs), one assigned to each section. Prior to grading the first process problems, the TAs met with the author for a training session in which they were introduced to the assignment, read over the guidelines and example problem provided to students, and reviewed Hanson and Williams' initial grading rubric. After some discussion, minor changes were made to the rubric in an attempt to better align the rubric with the problem guidelines. After the first set of process problems had been collected, both TAs and the author met again to practice using the rubric to grade a small set of actual student submissions; afterward, they discussed their rationale for assigning each grade, especially in cases where graders assigned different scores to the same submission. During this process, minor changes were made to the rubric as necessary to better align scores among the graders while maintaining adherence to the assignment guidelines. This process continued until consensus was reached and all overall scores were within one point of each other for three submissions in a row. Meetings between the author and TAs continued periodically throughout the span of the course to continue to monitor consistency among rubric scores; in all cases, overall scores were within one point of each other, and no further changes were made to the rubric.

2) *Fall 2011 at Large Mid-Atlantic Public Institution (LMAP)*

The Fall 2011 implementation at the LMAP institution was a close replication of the quasi-experimental portion of the pilot study. This implementation was conducted at the same institution with the same instructor who taught the EX1 and C1 sections during the pilot. The two sections participating were again taught back-to-back during the same time slots with the same maximum capacity of 155 students; however, the intervention was assigned to the section in the opposite time slot as chosen for the pilot in an effort to improve the internal validity of the study by controlling for types of students who might self-select to be in the earlier section. The experimental section for Fall 2011 at LMAP, EX3, again completed thirteen process problems for homework over the course of the semester at a rate of approximately one per week. The process problems during this implementation were again typed, but the files were turned in via an online course management system to lessen the burden placed on students who had limited access to printers. The instructor weighted the process problems to count 5% of the total course grade. Lecture content, tests,

traditional homework problems, and the comprehensive final exam were all common to both EX3 and the control section, C3.

The process problems were graded by a new graduate teaching assistant during Fall 2011 at LMAP. This TA went through a similar training process as the previous TAs using the updated rubric and guidelines. During the initial training session and follow-up meetings during the semester, overall scores on the graded process problems were consistently within one point of the researcher who oversaw the training.

3) Fall 2011 at Large Southeastern Public Institution (LSEP)

This implementation took place at a large, public research university located in the southeast United States. Similar to LMAP, the LSEP institution offers a wide range of degree programs at the undergraduate and graduate levels, and its engineering college has the largest portion of undergraduate enrollment. Statics at LSEP is offered through two different engineering departments. An academic year comprises two semesters, and students commonly take the course at the beginning (fall) of their second year.

The Fall 2011 implementation at LSEP followed a quasi-experimental design using one experimental section, EX4, and two control sections, C4a and C4b, taught by the same instructor and offered by the same department. The instructor for the three sections was a teaching assistant professor with considerable experience teaching the course. One additional section offered by the department, taught by a graduate teaching assistant, did not participate in the study. All three sections involved in this implementation were taught in a traditional lecture style format three times per week for 50 minutes. Since section EX4 was also offered as a distance education class, it consisted of a standard lecture delivered to approximately 60 on-campus students in person and was broadcast synchronously to its online students. Sections C4a and C4b contained approximately 100 and 130 students, respectively. Students in sections EX4, C4a, and C4b had common lectures, quizzes, four tests, a comprehensive final exam and homework assignments consisting of traditional workout problems collected once per week. Students in section EX4 were assigned six process problems over the course of the semester at a rate of approximately one every two weeks at the request of the instructor. Students wrote process problems only for problems that they were asked to work out for homework. To help compensate for additional time spent writing the process problems, students in section EX4 were assigned one less traditional workout problem on weeks when they completed a process problem. The process

problems were typed into a text box on the course's online management system, and they were weighted a small portion of the 10% of the overall course grade reserved for homework.

The process problems at LSEP were graded by a graduate teaching assistant assigned to the course. The teaching assistant was trained in a similar fashion as the LMAP teaching assistants although in this instance the training was conducted online via a webcam. Throughout the semester, graded problems were periodically monitored by the researcher who oversaw the training to ensure consistency. During the initial training and monitoring, the TA's scores were consistently within one point of the researcher's scores.

4) Spring 2012 at Small Mid-western Private Institution (SPri)

This implementation took place at a small private teaching institution located in the Midwestern United States. The SPri institution specializes in engineering, science, and math and offers degrees through the master's level, though over 90% of the students are undergraduates. Statics at SPri is offered through two different engineering departments. An academic year comprises three quarters, and students commonly take statics during the third quarter (spring) of their first year.

The Spring 2012 implementation at SPri consisted of two experimental sections, EX5a and EX5b, offered through the same department and taught by the same instructor. The instructor, an associate professor with considerable teaching experience and numerous teaching awards, requested that both sections receive the intervention to promote consistency. Thus, there was no control group for this implementation. EX5a and EX5b, each containing approximately 20 students, were the only two sections of statics offered by this department during the spring quarter. Classes for each section were taught four days per week for 50 minutes and featured a blend of lecture content, interactive demonstrations, and group work. The class meetings, homework problem sets, quizzes, two tests, and comprehensive final exam were common to both sections. Each section was assigned a total of 8 process problems at a rate of approximately one per week over the course of the term; homework sets consisting of traditional workout problems were assigned and collected approximately twice per week. Students wrote process problems only for problems that they were asked to work out for homework. The process problems were typed and turned in via hard copy during class meetings. Prior to the first process problem assignment, the instructor led students through the assignment instructions and grading rubric during class, and students were given some practice writing and grading

the problems. The process problems were weighted the same as a traditional workout problem within the homework set, and the total homework average counted 20% of the overall course grade.

The process problems at SPri were graded by two undergraduate teaching assistants assigned to the course. These TAs were identified by the instructor as being high-achieving students while taking statics and in subsequent courses. The two TAs were trained in person in the same fashion as the TAs at other schools. Scores among the TAs and the researcher conducting the training were consistently within one point of each other. Rather than a single TA being assigned to grade for each section, the two TAs alternated weeks, grading the process problems from both sections during their week. The graded problems were periodically checked by the researcher to ensure consistency in grading during the term.

5) *Summary of Participants and Settings*

The sections participating in the study can be added to the project timeline and summarized in the following table. Note that sections have been labeled such that ‘EX’ corresponds to experimental sections receiving the process problem intervention; ‘C’ corresponds to control sections. Experimental and control sections taught by the same instructor during the same term have been numbered identically to highlight that aside from the process problems, course elements like tests, final exams, workout homework problems, and quizzes were the same.

TABLE 2. PROJECT TIMELINE WITH PARTICIPATING SECTIONS.

Term	Institution(s)	Participating Sections
Spring 2011 (Pilot)	Large Mid-Atlantic Public Institution (LMAP)	EX1, C1 EX2 (different instructor)
Fall 2011	Large Mid-Atlantic Public Institution (LMAP)	EX3, C3
	Large Southeastern Public Institution (LSEP)	EX4, C4a, C4b
Spring 2012	Small Mid-western Private Institution (SPri)	EX5a, EX5b

D. Data Collection Procedures

As noted above, this study collected quantitative and qualitative data during each implementation of the intervention. Below is a summary of each of the data sources, followed by an explanation of the data collection process during each implementation.

1) Statics Concept Inventory

The Statics Concept Inventory (SCI), also known as the Concept Assessment Tool for Statics (CATS), is an inventory of 27 multiple-choice questions that involve conceptual reasoning related to statics topics but no significant computation (P. Steif & J. Dantzler, 2005). The questions comprise 9 distinct concepts, including free body diagrams, equilibrium, static equivalence, friction limit, and the representation of forces between contacting or connected bodies (Paul S. Steif & Hansen, 2007). This test was chosen to provide a quantitative measure of conceptual knowledge related to statics at the end of a term. The CATS was also used as the pretest during the pilot implementation to establish a baseline measure of conceptual knowledge among incoming students; however, this practice was abandoned in favor of using the Force Concept Inventory for reasons explained in the paragraph below.

2) Force Concept Inventory

The Force Concept Inventory (FCI) comprises 30 multiple-choice questions intended to measure one's understanding of Newtonian force along 6 different "dimensions", including kinematics, Newton's First, Second, and Third Laws of Motion, the Superposition Principle, and kinds of force (Hestenes et al., 1992). The decision to administer the FCI rather than the CATS as the pretest during the Spring 2012 implementation was made at the recommendation of CATS creator Paul Steif, who believed the FCI to better discriminate student knowledge at the beginning of a statics course (Paul Steif, 2012). Thus, the FCI was used to establish a baseline quantitative measure of conceptual knowledge related to Newtonian mechanics, which is "the most relevant prerequisite subject in physics" for students beginning in statics (P. S. Steif & Dollár, 2012, p. 5).

3) Student Grade Data

De-identified grade data was collected from each instructor for all students in the participating experimental and control sections after the end of the term. Records typically included grades for traditional and process problem (if applicable) homework assignments, quizzes (if applicable), tests, and final exams, as well as final numeric grades and assigned letter grades. Before the grade data was sent to the researchers, the instructor linked scores from any concept inventories taken during the term to the appropriate grade record once final grades had been assigned.

4) Student Survey

A short survey was sent out to all students involved in the study during each implementation near the end of the term. The survey was primarily used as a screener for possible interview participants and to help characterize each

section population. Questions asked students to report their statics enrollment history, goals and time spent on the course, perceptions of the process problems (if applicable), some demographic information, and an invitation to be contacted to participate in an interview.

5) *Interviews with Students*

Semi-structured interviews were conducted in person with students from experimental and control sections near the end of each term for each implementation. Students were purposely selected to participate in an interview based on their reported course enrollment history and current section when the number of volunteers was sufficient to allow for such sampling. A general goal was set of having five interview participants from each section during each implementation, with a comparable number of students who were first-time takers and those who were not. The interview protocol comprised questions investigating the student's experiences in statics and perceptions of the course, what topic they found most difficult during the term, and their perceptions of the process problems. Students in control sections were told about the process problems if they had not heard of them previously and were asked questions similar to students in the experimental sections. Each interview also contained a think-aloud portion in which the student was given a statics problem and asked to discuss their thought process as they went about setting up and solving the problem. Questions to probe their explanations were also asked. The interviews lasted approximately 30-40 minutes and were all audio-recorded for later transcription.

While the general content of the interview questions did not change throughout the study, there were some minor changes made to the protocol after the pilot study implementation. Specifically, a question was added asking students to list the major concepts covered in the course. This was aimed at helping to identify whether students tended to view each topic presented in the course as either unique or related through some conceptual relationship. Additionally, questions were added to gauge students' perceptions of their abilities as writers and the value they placed in completing writing assignments like the process problems. The interview protocols used for the pilot study can be found in Appendices B1 and B2, corresponding to the protocol for students in experimental and control sections, respectively. Participants from both experimental and control groups were given the same handout shown in Appendix B3 during the think-aloud portion of the interview. The revised experimental and control interview protocols can be respectively found in Appendix B4 and Appendix B5. The handout given to students did not change.

6) *Spring 2011 (Pilot) at LMAP*

Students in all participating sections were given an assignment by their instructor to take the CATS during the first week of the course. The test was accessed outside of class via an online system managed by the test's creator, Paul Steif. Students were asked to take the test on their own without the assistance of any resources. To encourage students to make an honest attempt to answer the questions to the best of their ability, they were told that they would receive full credit for completing the CATS with a score better than 20%, which would prevent passing scores due to random guessing. In reality, all students received credit equivalent to a single homework assignment just for completing the test regardless of their score. The instructor was given a list of names of students who took the test but was not given the actual scores until after final grades for the term had been submitted. During the last week of the course, students were assigned to take the CATS again using the same procedures.

Approximately three weeks before the end of the course, the researcher emailed students a link to the student survey. Participation was completely voluntary, and the instructor was not aware of any student's decision to participate. Based on the results of the survey, students were contacted to participate in interviews, which were scheduled and conducted during the last two weeks of the term. Two different interviewers, one assigned to EX1 and C1 and the other assigned to EX2, conducted the interviews using the same interview protocol.

After the assignment of final grades for the term, instructors were given the scores for their students on each deployment of the CATS as well as the names of any students who had consented to have their interview transcript linked to their grade file. The instructors added CATS scores into the grade book before deleting all personally identifying information except for the interview participants who had consented. Upon receipt of the grade books, the researchers replaced the actual student names remaining with pseudonyms.

7) *Fall 2011 at LMAP*

During this implementation, students were not assigned a concept inventory to take at the beginning of the course due to scheduling problems. Students were assigned the CATS near the end of the term using the same procedures outlined for the pilot implementation. The distribution of the student survey, scheduling of interviews with students, and collection of grade data after the term ended also followed the same procedures as used in the pilot.

8) *Fall 2011 at LSEP*

Students were not asked to complete the CATS at the beginning nor end of the term during this implementation. This was done at the request of the instructor, who used selected problems from the CATS as well as questions created in their likeness as 14 of the questions on the course's final exam. As a result, grade data was collected at the question level for the final exam during this implementation so that the subset of fourteen questions could potentially serve as a proxy for actual CATS data. Collection of the rest of the usual grade data remained unchanged.

The student survey sent out during this term comprised a combination of questions from the researcher's original survey and the instructor's end of course survey. This decision was made again at the request of the instructor who did not want students to receive two different surveys. As a result of the survey changes, in addition to other communication and scheduling problems, only one interview was completed during this implementation.

9) *Spring 2012 at SPri*

Students were asked by their instructor to complete the FCI at the beginning of the term during this implementation. Students took the FCI via an online system managed by researchers at Purdue University and were again asked to take the test without the help of any resources. Students were told that they would receive credit equivalent to a single homework assignment simply for completing the test. Again, the instructor was given a list of names of students who took the test but was not given the actual scores until after final grades for the term had been submitted. During the last week of the course, students were assigned to take the CATS using the same online system and procedures.

The student survey was sent out by the instructor near the end of the term. Although the instructor encouraged students to participate in the survey, students were reminded that participation was voluntary and that the instructor would have no knowledge of their decision to participate. Interviews were scheduled and conducted with students the following week.

10) *Summary of Data Collection*

Data collection for each implementation is summarized in Table 3. Due to the issues described above and the resulting loss of significant portions of both the quantitative and qualitative data, the Fall 2011 implementation at LSEP was ultimately not included in the analyses conducted for this study.

TABLE 3. DATA COLLECTION SUMMARY.

Term	Institution(s)	Participating Sections	Quantitative Data Collected			Qualitative Data Collected
			CI Pretest	CI Posttest	Student Survey	Interviews
Spring 2011 (Pilot)	LMAP	EX1, C1 EX2	CATS	CATS	Yes	Yes
Fall 2011	LMAP	EX3, C3	None	CATS	Yes	Yes
	LSEP	EX4, C4a, C4b	None	Limited	Limited	Very Limited
Spring 2012	SPri	EX5a, EX5b	FCI	CATS	Yes	Yes

E. Data Analysis Procedures

Given the differences in the participants, setting, implementation, and/or data collection among each of the implementations, quantitative data (linked to RQ2b) were analyzed at the implementation level. The qualitative data (linked to RQ1, RQ2a, and RQ2ai) were first analyzed at the implementation level; however, the results are reported at the study level since common themes were seen across all implementations.

1) Quantitative Analysis Procedures

Quantitative data for each case were analyzed using the IBM® SPSS® 20 statistical package. Descriptive statistics for each section were first computed and each variable was examined for normality. Based on the results of normality tests, parametric and/or non-parametric statistical tests were chosen as appropriate to answer each of the research questions.

2) Qualitative Analysis Procedures

The audio-recorded interviews for each case were fully transcribed and then analyzed using a three-stage process depicted in Figure 2 below. Each of these stages is described in more detail in the sections below.

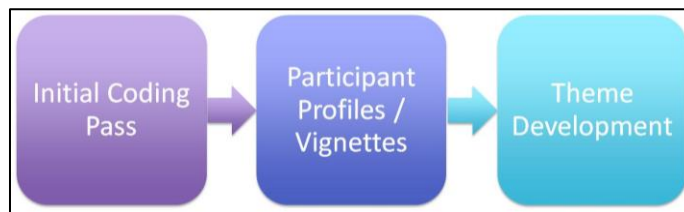


Fig. 2. Qualitative Data Analysis Process Overview.

a) Initial Coding Pass

The initial coding pass attempted to identify areas in the transcripts where students demonstrated conceptual and/or procedural knowledge, as these were hypothesized to be potential products of the process problem intervention as stated in the research questions. As coding began, however, the frequency of these two codes was low, likely because of the types of questions that were asked in the interview. However, there did appear to be clear differences in the ways that students discussed learning in the course. Thus, the two codes were expanded to include not only instances in which students demonstrated each knowledge type, but also statements in which they discussed a desire and/or preference for learning that type of knowledge. The two codes, described in detail in Table 4 below, were then used to code all of the interviews. To help establish credibility and minimize bias, an additional coder used the same code descriptions to code a subset of the pilot study interviews with high agreeability. The coding process remained unchanged for the rest of the data.

TABLE 4. CODE DESCRIPTIONS FOR INITIAL CODING PASS.

Code	Description of Code	Possible Evidence of Code
Conceptual Knowledge (CK)	Statement provides evidence of possessing conceptual knowledge and/or a conceptual approach to learning content (do not tag solely based on the usage of the word "concept" or similar). May also be used to tag incomplete or incorrect conceptual knowledge.	Making connections among different ideas, facts, problems, etc. Emphasis on meaningful understanding of course content; possibly links procedure to theory (understands why a particular solution works). Approaches problem solving using fundamental scientific truths, laws, theories, etc.
Procedural Knowledge (PK)	Statement provides evidence of possessing procedural knowledge and/or a procedural approach to learning content. May also be used to tag incorrect or incomplete procedural knowledge.	How to perform a problem solution and/or the "steps" needed. Emphasis on process and how a problem is done. Approaches problem solving algorithmically (uses series of steps that guarantees a correct solution) and/or heuristically (a structured, yet not predetermined approach that may provide a correct or near-correct solution, e.g. trial and error, rule of thumb, working backward, looking at examples, solving a more general problem first, etc.)

In addition to the codes described in Table 4, the researchers also highlighted interview passages that seemed particularly important or significant with respect to the study goals as consistent with an open-coding process (Seidman, 2006). This was aimed at limiting researcher bias by remaining open to explanations alternative to those supported by previous literature and/or quantitative findings. Any possible answers to the research questions that were adequately substantiated by the qualitative data were considered.

b) Participant Profiles

After the initial coding pass was completed, each interview transcript was condensed into passages summarizing each participant's responses to the four major parts of the interview:

- learning approach/beliefs about the course, especially the way they tended to approach learning (conceptually/procedurally)
- what topic(s) they found most difficult and why
- perceptions of the process problems, especially how they felt they used them, did or did not benefit from them, and how they think other students would or would not benefit from them
- how they completed the think-aloud problem, especially if they were successful with the problem, the way they talked about starting and working through the problem (evidence of conceptual backing or just rote procedural steps), and how they responded to probing questions regarding free-body diagrams, reactions, etc.

When crafting these participant profiles, full interview transcripts were reread, paying particular attention to lines that were coded and highlighted during the initial coding pass. Participant quotes were used throughout the profiles to illustrate appropriate context and to provide supporting evidence for the summary.

c) Theme Development

Once the participant profiles were created, they were reviewed and analyzed for themes common across participants for each part of the interview. For example, the summaries of how each student perceived the process problems were read and investigated for patterns. Additionally, themes across two or more interview sections were also considered, looking for potential interactions between them.

3) Mixed Data Analysis Procedures (Study-level)

Once the qualitative and quantitative analyses for each implementation were completed, the results from each implementation were mixed and considered together as consistent with a convergence model triangulation design (Creswell & Plano Clark, 2007, pp. 62-65). The researcher compared and contrasted findings from each data source and in some cases used the richer qualitative data to explain the quantitative findings. From this level of analysis, interpretations based on mixed findings were discussed.

F. Considerations of Rigor and Trustworthiness

Evaluating quantitative and qualitative research studies involves the consideration of comparable, yet different criteria intended to “establish that the results provide convincing evidence sufficient to answer the research questions” (Borrego et al., 2009, p. 60). In quantitative studies rigor is evaluated by considering: the validity of the study design, particularly its ability to control and/or randomize factors that could influence the results; the reliability of the data collection process and instrument(s), which should give consistent, repeatable measurements; the generalizability of the findings, usually achieved through random sampling of a defined population; and the objectivity of the researcher as a neutral observer (Lincoln & Guba, 1985, pp. 290-293). In qualitative studies trustworthiness is evaluated by considering: the credibility of the findings, enhanced through techniques like triangulation and/or member checking; the dependability of the data collection methods and tools, which may change intentionally or otherwise over the course of a study and should be documented accordingly; the transferability of the findings to other contexts, achieved through thick description of the settings and participants such that readers may determine its appropriateness; and confirmability of the findings, usually supported by an audit trail detailing the conversion of raw data to findings and including a discussion of researcher bias that may have influenced the findings (Borrego et al., 2009; Lincoln & Guba, 1985, pp. 294-301). For mixed-methods studies such as the one detailed here, Creswell and Plano Clark recommend “report[ing] and discuss[ing] validity within the context of both quantitative and qualitative research” (2007, p. 146). The following sections will summarize the efforts made to ensure the trustworthiness and rigor of the data collection and analysis procedures for this study.

1) Internal Validity and Credibility

Triangulation is a major source of enhancing the validity and credibility of the implementation-level and study-level findings. This is sometimes referred to as “triangulation validity” when findings drawn from both methodological data sets converge toward similar conclusions (Creswell & Plano Clark, 2007, p. 146). In addition, at the implementation level, the order in which the qualitative and quantitative data sources were analyzed was alternated to minimize the potential for any one source to bias the overall results.

Steps were also taken to independently ensure the internal validity of the quantitative results at the implementation level. Although true random assignment of the treatment (the intervention) was not possible, pre-test data was collected in Spring 2011 to help establish the similarity of initial conceptual knowledge between the groups within the same quasi-experimental setup, a process referred to as “matching” (Olds, Moskal, & Miller, 2005, p. 18). In an

effort to further control for the bias that may result from students registering for the earlier or later section time at LMAP, the treatment effect was applied to the alternate section time during the Fall 2011 implementation as was chosen in Spring 2011. At the instrument level, the concept inventories used were previously validated and subjected to peer review.

Steps taken to independently ensure credibility of the qualitative data at the implementation level include using purposeful sampling for interviews when the number of respondents made it possible.

2) *Reliability and Dependability*

Multiple implementations sought to establish the reliability of the quantitative data. Although not true, fully-controlled replications, the experimental design was repeated at LMAP under similar contexts. It should be noted that other implementations were conducted at locations with deliberately different contexts to help ensure the generalizability and transferability of the findings to a broader range of settings. At the instrument level, reliability of the FCI and CATS had been reported previously by their respective authors.

Dependability of the qualitative data at the implementation level has been documented in this chapter through a rich description of each of the settings and data collection procedures for each implementation, including explanations of why collection procedures varied across implementations. Interviews also followed a semi-structured protocol to allow for systematic investigation of answers to the research questions supported by synthesis of prior literature and the option for alternative explanations based on individual responses.

3) *Generalizability (External Validity) and Transferability*

Quantitative data collection targeted the entire population rather than a random sample of students in each section to help ensure that findings would generalize to each course section's population. The design of this experiment does not necessarily allow for the generalization of findings to a larger population (e.g. engineering students in general), as this would require random sampling from a larger number of institutions. However, the inclusion of varied institutional contexts provides one opportunity to explore how different populations respond to the same treatment.

Since the focus of qualitative studies is to characterize the experiences of specific participants within a particular context rather than looking for context-independent implications, the burden of evaluating how the findings from one study may transfer to different settings is generally placed on the reader (Lincoln & Guba, 1985, pp. 296-298). Rich descriptions of the settings and participants can help a reader determine the extent to which findings may transfer to

similar contexts. In this study, the settings and participant populations were described in detail in this chapter, and the selected participants will be described in more depth in the following chapters. When evaluating the transferability of the findings from this study to a different context, a reader might consider the level of similarity of the statics course size and sequencing in the curriculum, instructional approaches, student characteristics, etc. at their institution. Higher degrees of similarity would indicate a higher likelihood that the findings from this study would transfer to an alternate group of participants.

4) Objectivity and Confirmability

Objectivity was maintained in the collection of the quantitative data by utilizing data instruments that were developed by other researchers as one measure of conceptual understanding and by utilizing grades that were assigned by experienced instructors. The analysis of the quantitative data was conducted in accordance with established statistical methods.

Confirmability of this study is supported by the description of the process used to generate themes and conclusions from the raw interview transcripts provided earlier in this chapter. In the following chapters, themes will be supported by the participants' own words and direct quotations. The full audit trail containing raw data, coded transcripts, participant profiles, and thematic analysis is available upon request, subject to IRB approval and the provisions of the data management plan for this National Science Foundation sponsored study. A statement of researcher's background and identification of potential biases that may have influenced interpretation of the data is also given in Appendix C1.

IV. RESULTS

A. Introduction and Review of the Research Questions

The results will be presented in an outline consistent with the research questions, which are repeated below.

RQ1. How do students approach learning in statics with regard to conceptual and procedural knowledge development? (qual)

RQ2. What is the interaction between the process problems and conceptual knowledge development? (mixed at the discussion level)

RQ2a. How do students utilize the process problems with regard to ways that may work to develop conceptual knowledge, particularly through reflection? (qual)

RQ2ai. Do different learning approaches influence the way that students utilize the process problem assignments? (qual)

RQ2b. Do the process problems affect conceptual knowledge development? (quant)

Thus, the qualitative data collected from interviews with students will be presented first and sectioned into results for RQ1, RQ2a, and RQ2ai. Finally, results from the quantitative data collected to answer RQ2b will be presented. The discussion and interpretation of the results for RQ1 and RQ2 will be done in Chapter 5.

The qualitative data consist of interview conducted with thirty-two students. Thirteen students were from the Spring 2011 (Pilot) implementation at Large Mid-Atlantic Public (LMAP) institution, ten were from the Fall 2011 implementation at LMAP, and nine were from the Spring 2012 implementation at Small Mid-western Private (SPri) institution. The participants, broken down by section, are summarized in Table 5 using pseudonyms in place of real names.

TABLE 5. INTERVIEW PARTICIPANT LIST.

Implementation	Participants
Spring 2011 (Pilot) at LMAP	<i>Experimental Group (EX1):</i> Alex, Amy, Charles, Matt, Steve <i>Control Group (C1):</i> Beth, Melissa, Scott <i>Experimental Group (EX2):</i> Alan, Andrew, Kelly, Ralph, Randall
Fall 2011 at LMAP	<i>Experimental Group (EX3):</i> Aaron, Carly, Mark, Marley <i>Control Group (C3):</i> Ashley, Dustin, Henry, John, Kristen, Tori
Spring 2012 at SPri	<i>Experimental Group (EX5a/b):</i> Barry, Bill, Ezra, Frank, Jeremy, Jill, Kevin, Macy, Natalie

B. RQ1: Characterization of Student Approaches to Learning

During the interviews, participants discussed the different ways that they went about learning statics. Common among all participants were approaches that would be effective in developing procedural knowledge related to statics content, primarily practice carrying out statics-related mathematical procedures while solving problems. Students often commented on the importance of working problems as a way of learning statics. “It’s really just if you do it yourself; that’s when you know it,” explains Alex. Scott concurs, “In order to know the material, just actually doing it is very helpful.” All students seemed to place value both in developing procedural knowledge as a means of learning and correctly using procedural knowledge as an indicator of successful learning.

However, the participants varied in their description of approaches that would be effective in developing conceptual knowledge. While some seemed to purposely and effectively seek explanation as to why procedures worked or how similar content related to each other, others seemed to give little thought or effort toward these goals. To elucidate the differences between participants’ learning approaches, their responses to the interview questions were used to determine the degree to which they balanced conceptual and procedural knowledge development within the course. This is explained in greater detail in the sections below. The result can be depicted in Figure 3, which is a representation of possible student learning approaches, ranging along a continuum from a focus primarily on the development of procedural knowledge (on the left) to primarily conceptual knowledge (on the right). Although with this representation there could be an infinite number of positions along the spectrum, participants’ approaches seemed to cluster into four groups, which are categorized here as: procedure-centered, procedure-heavy, near-balanced, and balanced.



Fig. 3. Continuum of Student Learning Approaches.

It should be noted that eleven participants, approximately one third of the total, could not be characterized in terms of their learning approach since the evidence presented during their interview was either deemed not sufficient or not consistent enough to make a decision. Henry, for example, seemed to be a non-native English speaker and had a great deal of trouble communicating with the interviewer, which severely limited the quantity and quality of

interview questions that were included. Other participants tended to provide little elaboration on their responses, which alone did not give a clear indication of their learning approach. As an example, Tori talks about working problems as her primary learning strategy, and says, “I knew I was doing [a procedure] for a reason; I just didn’t know what that reason was.” However, she also believes that she “knew the concepts behind everything” and mainly had trouble with working out the procedures. Without further elaboration, conflicting responses like these are difficult to interpret. However, many of the participants with non-identified learning approaches seemed to lean toward the procedure side of the learning approach spectrum depicted in Figure 3.

It should also be noted that in addition to the groups presented in these results, learning approaches located further along the right side of the continuum shown in Figure 3 could also reasonably exist. These approaches would be characterized by a stronger focus on the development of conceptual knowledge with relatively less emphasis placed on the simultaneous development of procedural knowledge. In statics, approaches like these are not likely to be utilized due to a traditional focus of the course’s teaching and assessment on procedural aspects of statics knowledge. That is, a majority of statics pedagogy focuses on working example problems, and most assessment comes in the form of evaluating students’ solutions to problems. Some courses, such as engineering design as traditionally taught to freshmen, may naturally lend themselves to a larger emphasis by students on conceptual knowledge development. This is especially true of freshman design courses that focus on how to design with only limited opportunity to actually “do” design. Thus, the learning approach that students take in any course might reasonably be influenced by aspects of the course and the instructor. Still, there seem to be noticeable differences in the approaches taken by students in the data presented here, even when students are part of the same section.

1) Procedure-centered Learning Approach

Procedure-centered learning approaches are characterized by an almost exclusive focus on developing procedural knowledge while demonstrating little to no effort to also developing conceptual knowledge. Within this approach, working many problems, often using guess and check as a method of problem solving, is common, as is a focus on the “steps” or “pieces” of a problem. Students with a procedure-centered approach tend to use their course resources (books, internet) to search for examples similar to or the same as the problems they are solving rather than looking for underlying theory or explanation from the “content” portion of the source. Possibly as a result, they tend to report having difficulty using their procedural knowledge flexibly, especially on problems that they have not practiced.

Aaron, for example, talks throughout the interview about seeking out and applying step-by-step, algorithmic approaches for solving problems. According to him, he would usually study for tests by “just do[ing] problems until I saw enough of a pattern and enough of a set procedure to where I’d actually write out, ‘For this type of problem: step one, do this. Step two, do this. Step three...’” While this approach is useful for developing higher-level procedural knowledge, Aaron doesn’t seem to seek out understanding as to why his procedures work, and he seems to avoid learning about the concepts that surround the procedures. The problem ‘types’ that he mentions come from the problem’s physical placement in a textbook section rather than differentiated by relevant conceptual knowledge. As he works through the problems, he seems to use more of a guess-and check approach to generate his sets of procedures. “I would do the even [textbook problems] till I could get a system, and then, I’d go back and try to do the odd ones and see if the system matched the answers that were [provided by the book].” Aaron sums up his goal well by saying, “If somebody could give me a step by step process instead of just, ‘These are the concepts; here’s how they apply, and you just do it to everything and you’ll get the answer.’” When talking about the test problems, Aaron says, “You could come at it from so many different angles that I didn’t feel like that there was a set procedure established for how to solve each kind of problem.” “Most of them seemed kind of new to me. They definitely related; I mean, it was all the right concepts, but it would be problems out of the textbook with this extra little tweak to it, or there’d be something I’d miss, or I would do something backwards.” Based on these responses, it seems that Aaron’s step-by-step approaches were not flexible enough to be used on problems that he perceived to be different.

Charles says of his studying habits, “Usually I just do the homework. And then before the test I’ll go and I’ll go do all the WileyPLUS problems again to make sure I know how to do those...and then I’ll usually just go through the book and...I’ll just do practice problems out of the book.” Charles also mentions using guess and check approaches when submitting multi-part problems online: “I’ll fill out the first and answer and just click submit and see if that’s right to see if I’m doing it right”. Yet, he does not seem to combine this approach with other actions that would result in deeper understanding. When asked what he does once he gets a correct answer to a difficult problem, he says, “Just celebrate I guess.” This may indicate that Charles does not spend much time trying to understand why his eventual correct solution works. Possibly as a result, Charles describes test problems as “entirely new” compared to those he has worked previously for homework, saying of the test problems, “I feel that it’d just be hard to just figure that out in such a short amount of time.”

Melissa also seems to apply guess and check approaches when solving problems. She says, “I’m not one of those people who can like look at it and be like ‘oh, this is what I need to do.’ No. It takes me like a couple of times to like mess up and realize that.” She studies for tests by working through tests from prior years and redoing recent homework problems. According to her, “reworking homework problems from scratch...helps me figure out how to do [them] again”. This may indicate that Melissa, similar to Charles, is not successful at gaining understanding as a result of completing her homework, possibly applying procedures without regard to why they are appropriate. Yet, she continues to use this approach, saying, “Pretty much I don’t know what else I can do to study.”

Beth, explaining why she chose not to read her book, says, “I didn’t find it difficult to read, I just felt like it was more worth my time to look at the examples and just see in context how it was used rather than like read about it.” This focus on procedure without relevant conceptual knowledge, though, seems to have become a problem for Beth. When talking about trusses as her most difficult topic, she states, “I knew how to execute but I didn’t know why... I didn’t know what was happening; like why are we cutting the bar? And like what was the purpose...?” This missing conceptual knowledge that would answer questions like these seems to leave Beth unable to determine what procedures are appropriate to solve the problem at hand. She talks about this again when reflecting on the difference in her performance this semester vs. the first time she took the course, saying, “This time I know how to break down the problem, I know what formulas to use. I just – I don’t know, there’s some breakdown...” However, she does not seem to make the connection that the “breakdown” might be related to her primary focus on examples.

Steve describes his approach to completing homework problems as follows: “I would just try to go through my lecture notes, see if there’s a similar problem to that and follow it from there. And if not, then I would try to look [at] the book, but I don’t think the book was really useful. It doesn’t really have a good description about the subject, like how to solve like enough solution examples.”

2) *Procedure-heavy Learning Approach*

Procedure-heavy learning approaches are characterized by a primary focus on developing procedural knowledge, though participants in this category place some, though considerably less, effort into also seeking out conceptual knowledge. This learning approach is obviously similar in many ways to that of the procedure-centered students. Guess-and-check problem solving approaches are still very common, as is the tendency to study by working through many problems beyond what is required for homework. However, students with a procedure-heavy learning approach commonly at least acknowledge a need for understanding a problem to a greater degree or within some larger context

than just solving that particular problem, and they may make conceptual links among related material covered in statics or in a similar course like Physics.

For example, Frank says, “There’s like a straight forward way to study for this class, which I like. I like just a straightforward answer to everything.” Frank elaborates on his “straightforward” studying habits to reveal that he typically studies by working example problems online or problems from his instructor’s old quizzes and tests, which he cites as his most beneficial study tool. What distinguishes him from the procedure-centered students, however, is his recognition that the material he is learning in statics is related to material covered in his previous physics course and perhaps related to each other. Despite recognizing this connection, Frank reports that his background in physics is weak, and this may be preventing him from being able to make many links among related content from the two courses. When asked about the major topics in statics, Frank does identify equilibrium; however, it is unclear if he sees relationships among equilibrium and application topics like friction.

Like Frank, Alex also recognizes the link between physics and statics, saying, “Essentially what it felt like so far is an extension of Physics 1: Mechanics but applied to engineering concepts.” Yet, Alex seems focused mostly on the procedural elements of the course. While in class, for example, he says, “I don’t take any additional notes on the concepts because I go back and see how the problem is done and that’s generally good enough.” He says that working problems is “hands down” the most helpful method of learning for him, and he works problems from the book and internet in addition to his homework problems “so I wasn’t doing pattern repetition kind of thing”. The way that he approaches homework problems, though, seems guess-and-check at times. He identifies this as a problem with the online homework system used in the class, explaining, “You get 5 guesses; well, that’s exactly what they turn into is guesses. And you don’t really get that experience of having the instructor or a grader to go back and look at how you actually solved the problem.” The result is a studying approach that may not be ideal: “Usually if I follow up doing the homework like a week after and then go back and look at the notes if I need to, it can sometimes be hard, but it doesn’t take too long to look back and kind of figure out what happened.” While Alex does identify that equilibrium is a major topic of the course, he also says that identifying the major topics is “something I haven’t really thought about too much.”

Kelly speaks about the importance of understanding in statics, saying, “It’s more than just learn it by repetition. It’s actually understanding the concepts, which you can’t just do in the hour and fifteen minute class you have two times a week.” To supplement her time in class, Kelly says, “I found myself re-watching lectures from other

professors on problems and watching them and trying to understand how they're doing it and how they approach problems which, I think, is the hard thing about Statics.” Yet, she still seems focused on procedures and utilizing guess-and-check approaches when stuck on homework problems rather than searching for relevant declarative knowledge to assist her:

“If I don't understand it—if I'm really having a hard time—I usually go to through a process even if I don't know if it's right or not....Sometimes I'll think of another way to do it while I'm working on that part and then I'll [try it] two ways. If I understood, I'd be able to know the exact [process], but if I don't understand it, I usually think of different multiple things it could be. There are students who actually need to go through the process, see lots of examples, understand all the little pieces to grasp the whole entire thing. They can't just understand the broad aspect of why it is. I know I've asked the people who understand it. I've asked them well, like how did you see that? Like how did you just see that that was where you're supposed do something? And they said it just made sense and that was their reaction, they're like 'Well, I don't know how to teach that to you. I don't know how to show you that place, what I did, it shot right instantly to their brains and not mine that it just made sense then to do that.' And that was their explanation to me. They're like that's just what they would do and that was – that's the only way that you could describe it to me at least.”

Alan seems to mainly favor procedure when talking about how he best learns the course content. According to him, “The actual book material I didn't look through a whole lot. The homework is really what makes me learn it...and that's how I do in most of my classes is I just do the homework.” He mentions understanding as important though just not as difficult for him: “I think it's more just you have to practice and make sure you're doing the problem right and you have to make sure you understand how to do the problem that is important, but for me at least that wasn't the hardest part.” Instead, Alan identifies the “tiny mistakes” and “this magnitude of equations everywhere” as being his biggest problems. Yet, it is difficult to tell how accurately he is able to judge his level of understanding, and he comments that “Usually, I'll just look at a problem and then I'll just try to tackle it in any way I know how”, possibly indicating a guess and check approach.

3) *Near-balanced Learning Approach*

Near-balanced learning approaches are characterized by a primary focus on developing procedural knowledge, yet participants in this category also place considerable emphasis on also seeking out conceptual knowledge. Students

with a near-balanced learning approach still work problems as their primary means of learning, but they tend to work fewer beyond those assigned to them for homework. Homework becomes more than just a means of practicing procedures and is sometimes also used as an opportunity to understand why those procedures work and to relate them to content from this and other courses. Course resources are generally used to assist this process rather than only as sources of examples and procedures to mimic, which results in fewer guess-and-check approaches. Yet, students in this category still seem to favor the development of procedural knowledge over conceptual knowledge, especially when faced with frustration related to developing new conceptual knowledge or when they are performing well on course assessments.

For homework, Kristen talks about how she commonly looks at and uses problem solutions provided on Cramster, some of which were “the same basic problem but with different numbers”, when she is unable to solve homework problems on her own. In doing so, she replicates the solution procedures and applies them to her problem, sometimes using a guess and check approach; yet at the same time, Kristen tries to figure out “what are they actually doing?”, and in the case of problems that are not the same, “how do I translate that back to what I’m being asked?”. These statements suggest that Kristen is seeking out conceptual knowledge to complement her procedural knowledge. She gives another example of this when talking about calculating moments, specifically her attempt to reconcile the more “technical” approach of using “ r cross F ” presented in the textbook with the more “informal” approach of “just take the force; what’s the lever arm; is it counterclockwise or clockwise?” presented by her instructor. She says, “I was trying to use the book kind of as a supplement, but I couldn’t wrap my head around both the book and the way he was teaching it; I just couldn’t mesh the information together.” She consequently reports abandoning the book after some frustration “because it just wasn’t helping me”. Thus, Kristen’s desire for conceptual knowledge development, though present, still seems to fall secondary to her focus on procedure. The result of this can be seen when she talks about the major topics of the course, in which she describes a view consistent with strong procedural knowledge held together loosely by conceptual knowledge. She says, “I think for me it’s more of a step-by-step [process] because I’m still in the class and I still have to think of it kind of broken up into problems, but everything is surrounded; like the entire class is about equilibrium.” Thus, she appears to have been successful using her learning approach to develop relevant conceptual knowledge that may be used to connect various problem-solving procedures. She gives further evidence of this as her intention when she says, “I really feel like I have a grasp on the information that I’m supposed to know from listening in class and going over notes and then having that as a kind of a something to base my

problem-solving skills off of and see how it's done and then applying it to a different type of problem and understanding—actually understanding what's going on—what I'm doing.”

According to Kevin, “Just doing the problems is the most beneficial way to learn it really, just getting experience with different types of problems.” Yet, he seems to use the homework as an opportunity to further connect with content covered in class rather than treating it just as practice when he says, “So I mean most of the time [homework] just confirms what we have learned [in class] and I get like an actual feel of what we learned instead of just notes; I actually do something with it.” In addition to using the homework and his notes, he also mentions initially using the book to help understand and make connections among related topics with some success. He explains, “At the beginning of the year, I read the book a lot, but like once you get the basics, I felt like the stuff you build on to it is pretty easy to understand.” When asked about the major topics in the course, Kevin interestingly does not mention equilibrium, instead responding with “forces and moments, different ways of determining those pretty much”. While this is certainly a true statement, his response focuses only on the procedural aspects of the course and may indicate that he has not fully linked these processes to the concept of equilibrium to the same extent as Kristen.

Matt, taking the course for the second time, says, “Just practice more; that's really the only thing I've done [differently from last time].” He says that although he read the book, “the content of the subject material is very little compared to just how many pages of practice problems they have”, and he adds, “It helps to do the biggest variety of problems pertaining to whatever lesson you're on as possible, so you're prepared to answer whatever questions pertaining to that they can give you on the exam.” Although Matt seems to work many more problems than most of the other near-balanced students, he shows some evidence that he may be using the problems to relate to the content of the course since doing the problems “help[s] you get a better understanding of what's going on in the lesson”. Despite his primary focus on procedure and working problems, Matt does seem like he has been successful in developing some conceptual knowledge related to statics, evidenced by the connections that he makes among related content in statics and in other courses. He says, “I feel like a lot of people just don't understand that quite yet. They look at [statics] as like a bunch of different math word problems that they've never seen before when in fact, everything that we do in that class is completely related.” Matt, concurrently enrolled in a Thermodynamics course, also sees connections there: “I did find it really interesting when [statics content] crept over to Hydrostatics and so forth. It's straight up distributed loads; that's what it is.”

Scott, another repeat student, reports that homework is most helpful for him since “in order to know the material just actually doing it is very helpful”. However, Scott doesn’t mention working many problems beyond what is assigned for homework, and he studies for tests mainly by reviewing homework problems that he has already completed, focusing on the ones that he got wrong initially. Comparing this term to his previous attempt, he says that the course “was relatively easy the second time around as I knew most of the material”. As a result, he reports only “skimming” through the book to “refresh my memory” and attending office hours less frequently than before. He primarily attributes his success this term to going through the beginning content again: “It’s really like the first month of Statics, if you don’t get that, you’re lost for the rest of it...That was all the basic mechanics, the physics that goes into Statics that applies to everything from the first month onward.” It is with this material that Scott seems to have developed a good amount of conceptual knowledge, saying, “I got a much better grasp on that [material] than I did before.” The connections that he has been able to make since retaking the course seem to have helped his problem solving abilities, particularly on problems that he has not seen before: “I mean, [last semester] each problem was just kind of different, and I didn’t seem to make as many connections as I think I’ve been able to make since retaking the course. And with each problem seeming unique, you get to the test and you’re just confused because all of a sudden that thing is round and you have no idea what to do when its round.”

4) *Balanced Learning Approach*

A balanced learning approach is characterized by a focus on concurrent development of procedural and conceptual knowledge, making it difficult to determine which is emphasized more strongly. In fact, some of the participants in this category seem to view these two knowledge types as inseparable. Practice is still a necessary part of learning, but balanced students don’t practice just by going through the motions; rather, they view practice as a way of gaining deeper understanding of the content and relating to it in a different way. As with the near-balanced approach, course resources are used to assist in understanding the content, which is then used to help guide problem solutions. Connections among related material studied in this and other courses is common, which tends to allow balanced students to apply their knowledge to problems that they have not previously seen.

Ezra is a good example of this approach; when she was asked which of her three self-identified learning tools (homework problems, reading the textbook, and attending class/taking notes) were most useful to her, she is unable to choose just one. According to her, “Different parts provide different things; like going through the textbook allows me to learn the material at my own pace, going to lecture helps me pick out the important parts of the material, and

then doing the homework helps me apply the ideas.” She seems successful at being able to make connections among the various topics covered in the course, saying “to me it’s pretty much all the same and just static equilibrium”. Ezra gives another example of linking course content when she talks about her realization that couples are just “a special case of moments”. While she admits that when doing homework problems “you just kind of go through the motions a lot”, she also evidences her focus on understanding when she says, “Statics is something you can’t just try to fake, you actually have to think about it.” Ezra seems successful in the course, which she partially attributes to her Physics 2 class that included a section on static equilibrium. It also seems like her instructor may be driving this balanced approach through the way he “leads [students] to the concepts instead of just explicitly saying them” and structures their homework solution process.

Bill reports that going to class is the most useful learning tool for him since it is a time when he can get direct feedback from his instructor: “If we have a question about a problem, [the instructor] asks us to do it, how we think it’s supposed to be done, see what the answer is, and then if it’s wrong then he tells us why or how to do it [emphasis added] the right way.” Here, “why” and “how to do it” seem to reflect the simultaneous focus on conceptual and procedural aspects of the content, something that Bill also mentions he enjoys about the lecture portion of class. Bill also uses homework and the textbook to help his understanding by linking them back to classwork. He reports reading his textbook “to review what we’ve done in class” and says that “the homework...reinforces what [the instructor] is teaching”. Beyond the assigned problems and practice exams, Bill doesn’t spend time working extra problems: “The homework that he assigns is enough to learn the material better, so I don’t need to do additional homework problems.” His approach seems to allow him to apply his knowledge broadly; he gives an example of this when talking about moments, which he indicates as his most difficult topic initially. While he had seen moments in a previous course, he says, “Now I feel like I’m a lot better at just understanding the concepts and being able to apply it in many different situations, not just particular situations.” On the major topics of the course overall, Bill doesn’t mention equilibrium, instead saying that “[the course topics] all have to deal with forces and moments and stuff like that”. However, he does mention many of the application topics “lump[ing] under those two main things”.

Barry cites working problems as the most beneficial for him, particularly “...just trying to think through the problems and try and get an understanding of it on my own”. His goal of deeper understanding while practicing problems allows him to make connections among related content and procedures. When talking about his time in the classroom, he seems to look for both “how to do the stuff” and “what [the instructor] meant” when discussing the

content, an indication that he is focused respectively on both the procedural and conceptual aspects of the course. This seems to translate to a problem solving approach that can be flexibly used on similar problems, something that Barry explicitly mentions working toward: “If I can figure [a problem] out then I very rarely have issues with the similar problems again, whereas if I ask a friend for help they might give me help that’s too specific to that problem, so it doesn’t help me in the future on similar problems.” He also says, “Once I understand how to use [the formulas], I can apply them to everything that is thrown at me.”

John uses homework as his primary way of learning the material, but he seems to be searching for and making meaning of the homework problems. He says, “Just doing the homework, getting through it and mak[ing] sure you understand the process...; that’s the most important.” His focus on understanding seems to be driven in part by hearing “many stories about [using a solutions manual] and see[ing] people that have like done horribly because of it”. John still talks about using a “list of steps” and a “sort of flow chart in your mind” when solving some problems and the importance of practice, but he seems to balance it with a focus on understanding why particular solutions work. When stuck on homework, for example, John talks about looking at worked examples, but he also mentions “reading the text corresponding to [the example]”, which generally provides information about why certain procedures were used. He contrasts this to his approach at the beginning of the semester, when “I used to always just go for it and make it work” when solving problems. John also talks about the usefulness of his high school Physics background, which he feels made the transition into Statics easier for him compared to other students who took it in college.

Mark seems to balance the procedural and conceptual aspects of the course well. He talks about the homework as being especially beneficial to learning the material, but also mentioned that “lecture helped with learning the basics” and seemed to try to make connections between the two. When working on homework assignments, Mark said that his approach was “just kind of looking at it like not getting freaked out about ‘I’ve never seen this before-ish’ kind of thinking. How can I apply this to what we’ve learned?” In the beginning of the course especially, Mark tried to “make sure I understand what’s going on because I figured it would mostly build on the first stuff, which it did”. As Mark explained, statics was different than other courses in which “you can kind of get away with just kind of jotting down a couple of equations trying to figure out what this is; [for statics], it’s actually, do you know what you’re doing, and are you actually being like serious about this problem and thinking about what’s going on?” This effort to link the homework problems to lecture content may have helped Mark find commonalities among similar problems:

“Some of them are easier, some of them are harder, but once you kind of get in the swing of the entire section that we’re doing homework on, it’s not too bad.”

Andrew is one of the few balanced students that reports working some additional problems as a primary way of studying for the course, trying to “select problems that seem challenging”. He explains, “My approach is that if I can do the hard problems, then I would be able to do the easier one[s]...because the hard problems sometimes involve tricky parts or sometimes you really have to understand your concept of statics in order to solve.” Particularly, Andrew is focused on understanding the underlying assumptions made in setting up a problem, which indicates that he is linking his procedures back to the content. According to him, “You have to know your assumption, and it’s based on [a] scientific approach. Usually when I [make] bad assumptions I don’t get the right answer, but when I try to understand the problem... [it] actually helps in solving the problem.” In addition to making connections among related problems and statics content, Andrew also mentions, “Actually statics was kind of really related to the Physics course [I took in high school]; it involved vectors and it was actually fun.”

According to Amy, the most helpful for her with regard to studying for statics is “actually grasping the concepts and not just how to do one problem, but how to do them all”. This shows that she is actively trying to search for and create connections among different problems and the course content. This is her second time taking the course, and she contrasts her new approach with that of her first time in the course, saying, “[Most students] just try and learn the homework problems. That’s what I felt like I did last semester.” She goes on, “I feel like you don’t come in understanding the concepts. You come in wanting to do the homeworks and like figure out the math part of it because that’s basically all we’ve ever done as engineers.” Now, Amy works with a tutor to review course notes and work additional problems, though she says that they spend most of their time trying to “understand the concepts”.

Marley seems generally focused on understanding when it comes to statics. She says, “Right from the get-go, I was like I need to understand the basics in the beginning [of the course]”. Marley seems to have been influenced in this regard by older friends in her engineering sorority, who told her that it was difficult to catch up once you got behind and that future courses built on the foundation from this class: “It’s not something that I can make up for in the future, like just getting a passing grade and moving on to dynamics; I need to understand it when I move on.” She identifies assisting others as a major factor helping her learn for the course: “One of the major things that I think helped me from the beginning was teaching other people how to do it; like once I understood how to do it, I would

teach someone else what was going on and that really made it stick.” She also says, “Now I’m kind of seeing the big picture of how things work together.”

C. RQ2a: Utilization of the Process Problems to Develop Conceptual Knowledge through Reflection

The first part of RQ2 looks for instances of reflection prompted by completing the process problems. Despite reports by many participants that the process problems were not personally helpful, many still describe performing reflective actions as a result of completing the problems that may be useful in developing conceptual knowledge. These actions and explanations again seem to group into categories: self-explanation, checking understanding, organizing solution process, and generalizing solution process. However, these different categories do not necessarily represent a continuum as with learning approach.

1) Self-explanation and Relating Different Symbol Systems

Self-explanation, which includes translating figures, mathematical symbols, and operations into words, was the most common way that the problems were used. This is not surprising given the context and specific instructions of the assignment. Yet, it is a type of reflection that may not be explicitly performed, and likely not evaluated, without having to complete the process problems.

Kevin gives a useful description of self-explanation when he says, “I usually work out the actual problem and then sit down and stare at it and be like, ‘what did I do?’” This process was not always easy for him, and he acknowledges that in the beginning, “it is hard to take your math, I guess, ideas and put them down into words”. However, he reports that it became easier for him once he got used to the process: “I would say it improved my technical writing skills because I use a lot of terminology that most people wouldn’t understand if you weren’t taking statics or something.” In this way, we can see how Kevin uses the process problems to form relationships between mathematical processes and engineering-specific terminology. Likewise, Andrew, despite not finding the process problems very helpful, similarly says that he learned “how to try to convert the equations into words.”

Mark talks about using self-explanation in a slightly different way: “Just being able to put what you’re doing in words instead of -- like I said with other math classes, just putting in numbers and looking at the symbols -- you’re thinking about this is actually tension, this is actually gravity, there is something, the moment arm, and you can think about it in words and something that you can relate to as opposed to M, X [or] whatever else.” While he is relating engineering-specific terminology to mathematical symbols like Kevin, Mark also seems to be describing a connection between mathematical symbols and words that have physical significance in his mind.

Alex describes his approach as “essentially just typing into words what I have on the page where I worked out the problem”, yet also says that “when I write it I’m trying to think, ‘okay, these are the steps I take, and this is what you should look for’”. Here, “what you should look for” might represent some explanation of problem features and/or cues that prompt the use of particular procedures to solve the problem. Kelly also seems to go through this type of explanation, saying that she included phrases like “use this point because it’s the most convenient because you can eliminate forces”.

Although Alex reports that the process problems are not often useful to him personally, he also describes instances when they do cause him to think about a homework problem in other ways that he normally might not: “So for me, most of the time I don’t get very much out of it, but other times, when I slow down and think, it’s like ‘okay, I’ve got to explain this to someone else, how else can I explain it?’” Not only is Alex searching for explanation, he is also thinking about alternative ways of explaining a solution procedure, which might help him make meaningful connections between procedures and concepts. Randall similarly says, “I did something and then, explain[ed] that, explain[ed] why that’s important....So it did help with re-explaining to myself why I did what I was doing.”

2) *Checking Understanding*

Checking understanding was another common type of reflection that participants discussed while talking about the process problems. While this is similar in some respects to self-explanation, participants in this category seem to go beyond just describing symbols and processes as words and instead use the process problems as a way of validating their understanding of why particular procedures were used, or in some cases, seeking out that information. Thus, the focus moves from the mathematical solution to thinking about how/why the problem is solved, possibly linking procedures to concepts.

In terms of validating understanding, Carly puts it like this: “I feel like when people do the [homework] problems, they don’t always understand why they’re doing the steps they are. They might like just be looking at an example and copying every move or just doing what another student tells them, so [the process problems] did help me in terms of, okay, I went about solving this problem like this, now why did I do that and how can I explain my reasoning to another person?” Jeremy echoes this sentiment when he says, “Sometimes you do a number problem and you plug in the numbers. But whenever you do a problem without any numbers or without any diagrams or anything like that, you really understand it better, I think.” Rather than focusing on the numbers and answer to a problem, Jeremy also attempted to track his understanding: “This is why I have this conclusion, this is why I have this answer.” Jill seems

to go through this process even more explicitly. She says, “[I do] the calculation first and then I go back and then start like seeing how to apply the theories into it.” Thus, she is searching for connections between the specific solution procedures of the problem and the underlying declarative knowledge that supports their use. In a similar way, Matt explains, “[A process problem] forces students to think about the [homework] problem conceptually instead of mathematically.” This may explain why Alex chooses to write the process problem last: “So if you get to the first one and try to solve it and then try to write the process problem at the same time then you may not have the full understanding of how things go yet, even though you might have gotten the right answer. But once you do the rest of the homework problems then you pretty much have it figured out at that point and then it’s a lot better of a position to write the process problem.”

Kevin seems to contrast the type of knowledge he usually draws on to complete homework problems with that when completing a process problem: “a lot of times if you just have this math problem... you just kind of go through it and figure out your variables....To write about you can’t just be like ‘you have this formula’. You have to be like, you know, ‘for this to be in equilibrium, this has to be true’, and write stuff like that.” Here, he attributes meaning to why certain equations are used to solve the problem, and, hopefully, links the process of constructing equations to the concept of equilibrium. He says, “So... I mean you just have to actually understand what you are doing to write about it.” Many other participants echoed this sentiment. When asked why the process problems might be helpful for learning, Ezra comments, “You actually think about what you did. It helps students better figure out...how they solved the problem” Aaron similarly quips, “You really have to think about what you’re saying.” According to Marley, “[A process problem] forces people to stay with it enough to understand a little bit. You can’t write a process problem and not know what you’re doing... when I sat down [to complete a process problem], I had to know every little minute detail about [the problem].” Bill seems to expand on this idea even more when he says, “I guess it makes you think about actually what you’re doing so instead of just...doing it like it’s a habit, you gotta think about it a little more.” He also describes a time when completing a process problem made him revisit and change his mathematical solution: “I know I’ve actually corrected some of my problems, my math, based on going back over it and trying to type it out and realizing I missed something in the math or it just doesn’t look right, so I mean I guess that helps.”

Similar to the other participants in this category, Beth, a control group participant, says that she feels like the process problems “would just make me think about, you know, why am I doing this? Why [do] I need this number? How do I get it? What steps do I need to take to get it?” These are the type of questions that go beyond just

explaining a solution process and instead connect why certain solution procedures were used to the actual procedures themselves.

3) *Organizing Solution Process*

For some students, the process problems were an opportunity to return to their original work and organize their thoughts into a more coherent, logical chain of reasoning. Aside from just cleaning up work, the process problems help some students in this category take a disorganized, possibly confused solution process and refocus on what steps were actually necessary.

Marley provides a good example of how she went about organizing her work for the process problem when she says, “Usually I don’t get a problem right on the first time, so I would have like all of my messy work, and then I flip a new page and like do it out step-by-step and have each, like what I was going to put in this paragraph and this paragraph and that paragraph.” Ralph similarly says, “I would say that it’s really [that] people are able to get out their ideas out of their head and on the piece of paper.... Sometimes it gets messed up when you’re thinking about it so...sometimes it’s better to have it laid out...like an outline.”

For Ezra, this organization was “pretty much the only part I liked at all...as in, you had to get your thoughts organized and ready to write down.” She goes on to explain: “When you’re doing a [homework] problem you just kind of go through the motions a lot and then when you’re doing the problem you might figure out there’s a better way to do it and then... so you start going off on that path and...you might figure out that that path leads to a dead end or something, so you go on another path. So you might not take the most efficient route, but [when] you explain what you did, you already did the problem so you can kind of explain in a more organized manner.” John, a control group participant, concurs. “I think it would help organize my thoughts a bit because I – sometimes approaching a problem, I tried different ways of attacking it.” Kevin takes this approach: “[I] write down like every single thing I did and then if it seems like this was unnecessary then I will just delete it from my paragraph because if I did unneeded work and found stuff I didn’t really need.”

4) *Generalizing Solution Process*

Using the process problems to generalize a solution process, that is, generating a process that can be applied to a range of common problems rather than just the specific problem, is another type of reflection that students reported.

Amy says, “I really like [the process problems] because [they] make me sit down and think about the steps that I’d have to do for that [homework] problem, and then usually—like the steps—you could just manipulate them for all

other problems for that type.” Matt seems to agree, saying, “I feel like the point was you can take the [process problem] and just look at it and be able to apply it to every kind of problem that it covers for the chapter to a certain extent.”

John, a control group student, says, “For me, when I’m writing on my cheat sheet, what I do is I write down the process of solving a problem. For this type of problem..., do that. If it’s that sort of thing, then I can definitely see [the process problems] being useful.” Scott, another control group student, says that the process problems would be useful in “probably being able to make connections from one problem to a similar problem”. He explains, “Because in not just working through the math, but in having to write out the concept, it helps you to understand the concept that links different problems together of a similar nature, or even problems that build off of the kind of problem you’re explaining.”

5) *Little to no Reflection*

Some students seemed to go through little if any reflection as a result of completing the process problems. While these students still went through a translation process similar to that described by the self-explanation participants, students in this category don’t seem to reflect on their process in the same way.

Frank describes his approach to completing the process problems as follows: “I kind of just reworded [the example process problem] and then applied it to the problem...Then whatever grade I got, if it was a perfect score then I would just copy what I did and then just keep doing that and if I got a lower score than I did on the last one, then I would try to change it up a little bit more.” This seems to indicate that Frank is not going through much if any reflection on his process and instead applies a guess and check method similar to what other students use when completing traditional homework problems. Part of this seems to stem from Frank’s preoccupation with the problems not containing numbers or equations. When asked why he thought the problems might not have an effect on learning, he responds, “Well, one, they don’t have answers on them.” He also says, “I don’t really learn anything from it, it’s just kind of, feels too much like English class, just writing down what you’re thinking. I would rather just deal with an equation than I would writing an essay.”

Alan says, “I wasn’t really sure what they’re looking for. I would usually just write down whatever I thought would be good enough.” He goes on to say that he tended to not elaborate on his procedures very much. “I don’t know how much of the thought process I went through like I just kind of wrote down ‘and then you multiply this number by this number’. I’m not sure if I said ‘and then you examine the moment and see that it’s perpendicular

to...’ – I didn’t do a whole lot of that I guess.” Steve similarly focuses on superficial problem details, saying, “ I would solve it in a different paper then I would just look at the solution and what I wrote down and just write it down in a fancy way.”

D. RQ2ai: Interactions between Learning Approach and Utilization of Process Problems

A sub-question of RQ2a involved investigating possible connections between participants’ learning approaches and the types of reflection that they discussed engaging in as a result of completing the process problems. Table 6 provides a summary of this information. For reference, asterisks identify participants who reported taking the course previously, and control group participants are identified by a superscript “C”.

Among the participants whose learning approach was categorized, we can see that students from the ‘balanced’ and ‘near-balanced’ learning approach categories used the process problems the most and in the greatest number of ways. These students were also the only ones to use the problems to organize and/or generalize their solution process.

However, the problems generally prompted reflection from students across the full range of learning approaches, though Alan, Frank, and Steve are exceptions. Many of the students for whom their learning approach was not able to be determined still report reflecting on the levels of self-explanation and checking understanding.

TABLE 6. SUMMARY OF TYPES OF REFLECTION BY PARTICIPANTS

Learning Approach	Level of Reflection				Little to None
	Self-explanation	Checking Understanding	Organizing Solution Process	Generalizing Solution Process	
Balanced	Mark, Barry, Andrew	Marley, Ezra, Bill	John ^C , Marley, Ezra	John ^C , Amy*	--
Near-balanced	Kristen ^C , Kevin	Kristen ^C , Kevin, Matt*	Kristen ^C , Kevin	Matt*, Scott* ^C	--
Procedure-heavy	Alex, Kelly*	Alex	--	--	Alan, Frank
Procedure-centered	Charles	Aaron, Beth* ^C	--	--	Steve
Not Identified	Dustin ^C , Carly, Tori ^C , Ashley ^C , Jeremy, Ralph, Randall	Carly, Dustin ^C , Jill, Macy, Jeremy	Ralph	--	--

*indicates a student who reported being previously enrolled in statics
^Cindicates a student from a control group

E. RQ2b: Effects of Process Problems on Conceptual Knowledge Development

1) Spring 2011 (Pilot) at LMAP

a) Brief Review of the Implementation

The Spring 2011 (pilot) implementation at the LMAP institution included all three sections of statics offered during that semester. Two of the sections were used to set up a quasi-experimental design in which one section, EX1, received the process problem intervention while the other, C1, was used as a control. EX1 and C1 were taught by the same instructor back-to-back and shared the same lecture content, four tests, a comprehensive final exam, and homework assignments consisting of approximately six problems collected twice per week via an online system that accompanied the course text. In addition to the common homework problems, section EX1 was asked to complete thirteen process problems over the span of the course at a rate of approximately one per week. All students were asked to take the Statics Concept Inventory (SCI, or CATS) at the beginning and end of the term, though only the post-test results will be presented here since the SCI used as a pre-test is known to not provide meaningful information (P.S. Steif & Dollar, 2012); this was also confirmed during a previous analysis of this data set (Venters, McNair, & Paretti, 2012). The remaining section that participated in the pilot, EX2, was taught by a different instructor and had different lectures, homework assignments, tests, and exam questions than sections EX1 and C1. Thus, data from EX2 will not be included in this quantitative analysis since no meaningful control group exists.

The quantitative analysis presented here will begin with an investigation into the possible bias of the sample that may have resulted from students who self-selected to take the concept inventory. Results from each of the quantitative data sources will then be presented in turn.

b) Self-selection Bias Analysis

The self-selection bias analysis aims to answer the following question: Are students who self-selected to take the SCI reasonably representative of their section as a whole? Since the final exam was comprehensive, common to both sections, and not curved in the gradebook, it was chosen as the parameter on which to judge section representativeness. The analysis begins with the entire population of grade records collected for students enrolled in sections EX1 and C1, which by default excludes grade records for students that withdrew from the course before the semester ended. In addition, grade records that contained a grade of zero on the final exam were removed for this analysis since these likely represent students who stopped participating in the course. As shown in Table 7 below, this reduced the number of records by fifteen percent or less in each section.

TABLE 7. GRADE RECORDS FOR CONTROL AND EXPERIMENTAL SECTIONS (SPRING 2011).

Section	Total # of Students	Excluded Cases*	Remaining # of Students (% of total)
Control (C1)	99	13	86 (87%)
Experimental (EX1)	87	13	74 (85%)

*received a grade of zero on the final exam

Self-selection bias will first be explored in the control section in which 64 of the 86 students (74%) took the SCI. The histogram shown in Figure 4 below shows the distributions of final exam scores for students in section C1, separated into groups by whether or not they took the SCI. Table 8 summarizes the two groups and provides basic summary statistics for each.

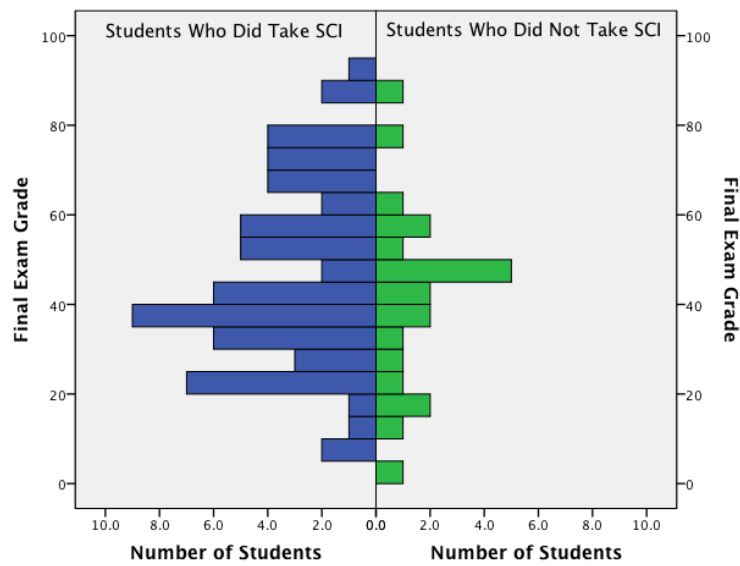


Fig. 4. Histograms of Final Exam Grades for Students in Section C1.

TABLE 8. SUMMARY STATISTICS OF FINAL EXAM GRADES FOR STUDENTS IN SECTION C1.

Group	N	Median	Mean	SD
No SCI	22	44.5	41.68	20.588
Took SCI	64	41.5	45.78	21.019

The histograms in Figure 4 appear to indicate that final exam grades for both groups of students in C1 approximate a normal distribution. Results from the Shapiro-Wilk test confirm that the distributions are normal for the group that took the SCI ($W=.976$, $df=64$, $p=0.239$) and for the group that did not ($W=.979$, $df=22$, $p=0.893$). Thus, the parametric t-test was used to compare the mean final exam score of each group. As shown in Table 8, the mean final exam scores for the two groups differ by about four points. The t-test confirms that the means are not statistically different between groups ($t=0.793$, $df=84$, $p=0.430$). Thus, the group of students from the control section that self-selected to take the SCI seems to be reasonably representative of that section as a whole.

Next, self-selection bias will be explored in the experimental section in which 52 of the 74 students (70%) took the SCI. Histograms showing the final exam grade distributions for the two groups in the experimental section can be found in Figure 5. Summary statistics can be found in Table 9.

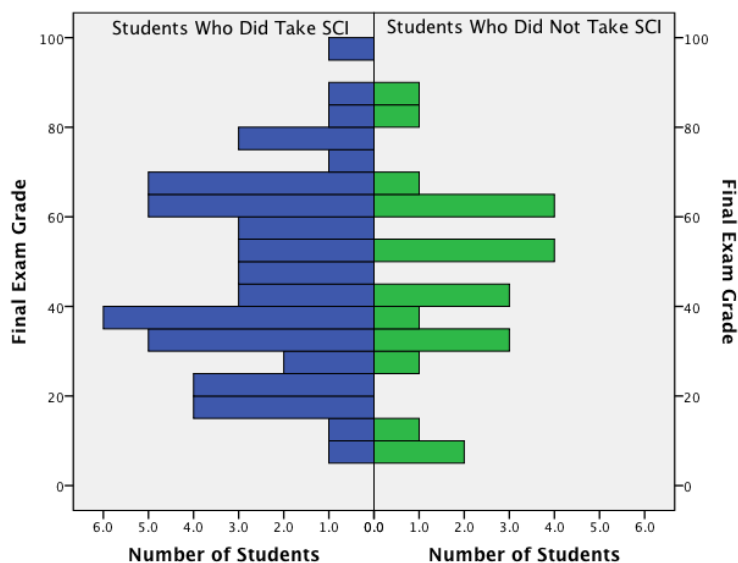


Fig. 5. Histograms of Final Exam Grades for Students in Section EX1.

TABLE 9. SUMMARY STATISTICS OF FINAL EXAM GRADES FOR STUDENTS IN SECTION EX1.

Group	N	Median	Mean	SD
No SCI	22	47	45.50	22.150
Took SCI	52	44.5	46.40	21.768

The histograms in Figure 5 appear to indicate that final exam grades for both groups of students in EX1 have a non-normal distribution. Results from the Shapiro-Wilk test confirm that the distributions are normal for the group that took the SCI ($W=.973$, $df=52$, $p=0.282$) and for the group that did not ($W=.972$, $df=22$, $p=0.758$). Thus, the parametric t-test was used to compare the mean final exam score of each group. As shown in Table 9, the mean final exam scores for the two groups appear to be similar. The t-test confirms that the means are not statistically different between groups ($t=0.162$, $df=72$, $p=0.871$). Thus, the group of students from the experimental section that self-selected to take the SCI seems to be reasonably representative of that section as a whole.

c) Statics Concept Inventory Results

To investigate the research question of whether the process problems affect student conceptual understanding, scores from the Statics Concept Inventory (SCI) were compared between sections. In addition to excluding records that contained zero on the final exam, excluding records that had zeroes on over half of the process problems further

reduced the number of students who completed the SCI by six in EX1, bringing the total to 46 (62% of the total class). Figure 6 shows histograms of the SCI score percentage for each section; summary statistics are provided in Table 10.

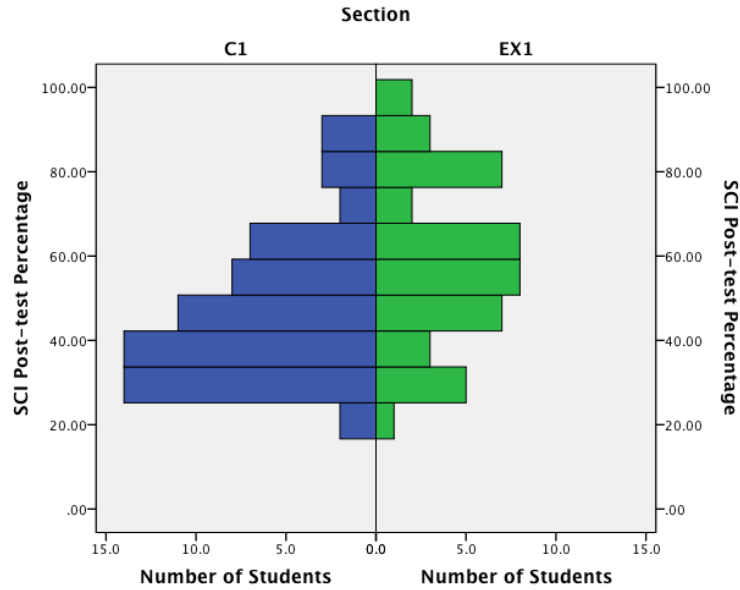


Fig. 6. Histograms of SCI Scores for Students in Sections C1 and EX1.

TABLE 10. SUMMARY STATISTICS OF SCI PERCENTAGE FOR STUDENTS IN SECTIONS C1 AND EX1.

Section	N	Median	Mean	SD
C1	64	44.4	47.6	17.257
EX1	46	59.3	60.1	20.289

The histograms in Figure 6 appear to show a non-normal distribution in section C1 and a normal distribution in EX1, and mean score percentages reported in Table 10 do not appear to be largely different from one another. Results from the Shapiro-Wilk test confirm that the distribution of SCI score percentages in section C1 is non-normal ($W=0.951$, $df=64$, $p=0.012$), and that the distribution for EX1 is normal ($W=0.971$, $df=46$, $p=0.297$). Thus, non-parametric tests were used to compare the locations of central tendency between the two groups. As shown in Table 10, the median final exam scores for the two groups appear to differ by approximately 15 percentage points. The Mann-Whitney U test confirms that the central tendencies of the two distributions are statistically different ($U=2005.5$, $n_1=64$, $n_2=46$, $p=0.001$). The Hodges-Lehman estimate of the difference between the medians of the two groups is 11.1 with a 95% confidence interval ranging from 3.704 to 18.519. This translates to a difference of 3 questions on the SCI with a 95% confidence interval of a difference between 1 and 5 questions.

Finally, possible correlations between process problem grades and SCI scores were explored. An average process problem grade was calculated for students in the experimental section and correlated with their post-score on the SCI if available. Tests indicated no significant correlation between process problem average and scores on the post-test of the SCI.

d) Student Grades

To investigate how process problems affect student performance in statics, course grades on tests and the final exam were analyzed. Again, records from EX1 were excluded if more than half of the process problems were not attempted as indicated by a score of zero. Tests for normality were first conducted in a similar manner to that described previously, and the results indicated that at least one section had a non-normal distribution of scores for Test 1, Test 2, and Test 4. Distributions for Tests 3 and the Final Exam were normal for both sections. Again, the parametric t-test was used to compare the mean scores between the two sections for items that were normally distributed; the non-parametric Mann-Whitney U test was used to compare distributions that did not meet assumptions of normality. The statistical test results for each item are shown in Table 11 below, along with summary statistics.

TABLE 11. SUMMARY STATISTICS AND STATISTICAL TEST RESULTS COMPARING STUDENT GRADES IN SECTIONS C1 AND EX1.

Item	Section	N	Median	Mean	SD	Test Statistic	df	p value
Test 1	C1	86	64	64.56	20.653	U=2632.5	--	0.454
	EX1	57	72	66.19	22.927			
Test 2	C1	86	58	58.07	19.694	U=2794.5	--	0.157
	EX1	57	65	62.00	23.017			
Test 3	C1	86	51	50.65	20.758	t=0.429	141	0.668
	EX1	57	53	52.11	18.322			
Test 4	C1	84	38	43.45	21.313	U=2938.5	--	0.022*
	EX1	57	50	52.18	22.989			
Final Exam	C1	86	42.5	44.73	20.866	t=0.831	141	0.407
	EX1	57	45	47.81	22.804			

As shown in the table above, the results from the analyses indicate that no statistical differences exist between sections EX1 and C1 with regard to scores on Tests 1, 2, 3, and the Final Exam. The Hodges-Lehman estimate of the difference between the medians of the two sections on Test 4 is 9 points with 95% confidence of a difference between 1 and 17 points. Thus, there appears to be no consistent differences in indicators of procedural knowledge between students that completed the process problems and those that did not.

e) Summary

In this implementation, students in the experimental section on average scored higher than students in the control section on the SCI, a measure of their conceptual knowledge of statics content. The difference in scores was statistically different ($p=0.001$) with an estimated difference of about three questions on the SCI.

The experimental and control groups were not consistently different with regard to measures of procedural knowledge (tests and final exam).

2) Fall 2011 at LMAP

a) Brief Review of the Implementation

The Fall 2011 implementation at the LMAP institution was a close replication of the quasi-experimental portion of the pilot study, conducted at the same institution with the same instructor who taught the EX1 and C1 sections during the pilot. The experimental section for Fall 2011 at LMAP, EX3, again completed thirteen process problems for homework over the course of the semester at a rate of approximately one per week. Lecture content, tests, traditional homework problems, and the comprehensive final exam were all common to both EX3 and the control section, C3. Due to scheduling problems, students in this implementation were not assigned a concept inventory to take at the beginning of the course due to scheduling problems.

As with the pilot study data, the quantitative analysis presented here will begin with an investigation into the possible bias of the sample that may have resulted from students who self-selected to take the concept inventory. Results from each of the quantitative data sources will then be presented in turn.

b) Self-selection Bias Analysis

As before, the self-selection bias analysis aims to answer the question: Are students who self-selected to take the SCI reasonably representative of their section as a whole? Since the final exam was comprehensive, common to both sections, and not curved in the gradebook, it was chosen as the parameter on which to judge section representativeness. The analysis begins with the entire population of grade records collected for students enrolled in sections EX3 and C3, which by default excludes grade records for students that withdrew from the course before the semester ended. In addition, grade records that contained a grade of zero on the final exam were removed for this analysis since these likely represent students who stopped participating in the course. As shown in Table 12 below, this reduced the number of records by ten percent or less in each section.

TABLE 12. GRADE RECORDS FOR CONTROL AND EXPERIMENTAL SECTIONS (FALL 2011).

Section	Total # of Students	Excluded Cases*	Remaining # of Students (% of total)
Control (C3)	90	9	81 (90%)
Experimental (EX3)	140	9	131 (94%)

*received a grade of zero on the final exam

Self-selection bias will first be explored in the control section in which 44 of the 81 students (54%) took the SCI. The histogram shown in Figure 7 below shows the distributions of final exam scores for students in section C3, separated into groups by whether or not they took the SCI. Table 13 summarizes the two groups and provides basic summary statistics for each.

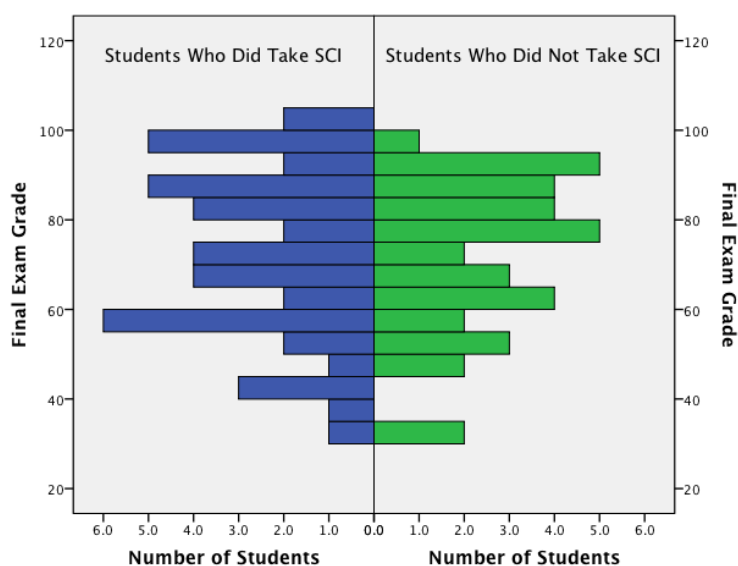


Fig. 7. Histograms of Final Exam Grades for Students in Section C3.

TABLE 13. SUMMARY STATISTICS OF FINAL EXAM GRADES FOR STUDENTS IN SECTION C3.

Group	N	Median	Mean	SD
No SCI	37	75	69.32	17.166
Took SCI	44	70	69.77	19.228

Visual inspection of the histograms shows that scores on the final exam appear to be normally distributed for both groups of students and that both groups have a similar distribution. The Shapiro-Wilk test confirms that the distributions are normal for both the group that did not take the SCI ($W=0.943$, $df=37$, $p=0.059$) and the group that did ($W=0.959$, $df=44$, $p=0.118$). Thus, the parametric t-test was used to compare the mean final exam score of each group. As shown in Table 13, the mean final exam scores for the two groups appear to be very similar. The t-test confirms that the means are not statistically different between groups ($t=0.110$, $df=79$, $p=0.913$). Thus, the group of

students from the control section that self-selected to take the SCI seems to be reasonably representative of that section as a whole.

Next, self-selection bias will be explored in the experimental section in which 83 of the 131 students (63%) took the SCI. Histograms showing the final exam grade distributions for the two groups in the experimental section can be found in Figure 8. Summary statistics can be found in Table 14.

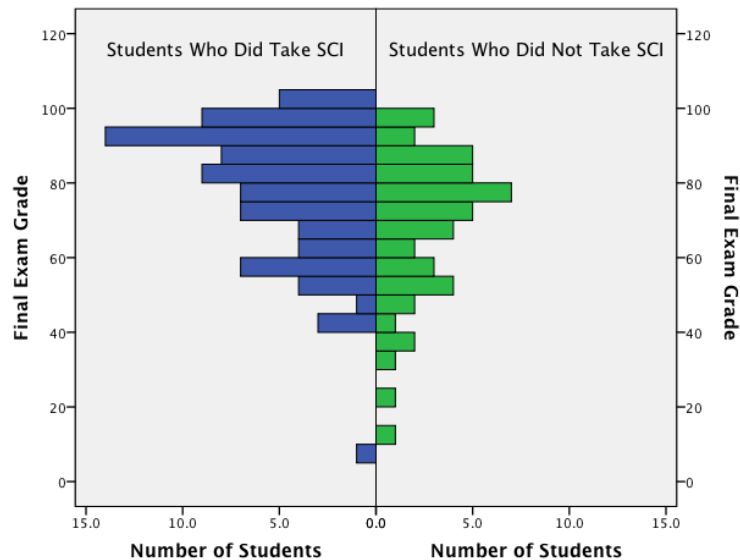


Fig. 8. Histograms of Final Exam Grades for Students in Section EX3.

TABLE 14. SUMMARY STATISTICS OF FINAL EXAM GRADES FOR STUDENTS IN SECTION EX3.

Group	N	Median	Mean	SD
No SCI	48	70	66.04	19.892
Took SCI	83	80	75.75	18.135

The histograms in Figure 8 appear to indicate that final exam grades for both groups of students in EX3 have a skewed distribution. Results from the Shapiro-Wilk test confirm that the distributions are non-normal for the group that took the SCI ($W=.919$, $df=83$, $p<0.001$) and for the group that did not ($W=.944$, $df=48$, $p=0.024$). Thus, non-parametric tests were used to compare the locations of central tendency between the two groups. The Mann-Whitney U test confirms that the central tendencies of the two distributions are statistically different ($U=1396.5$, $n_1=83$, $n_2=48$, $p=0.004$). Thus, as indicated in Table 14, the group of students who self-selected to take the SCI in section EX3 tended to score higher on the final exam than the rest of their section. The Hodges-Lehman estimate of the difference in medians between the two groups is 10 points, with a 95% confidence interval of a difference between 5 and 15

points. This may indicate an overrepresentation of stronger students taking the SCI that section, which may serve to artificially inflate the average SCI score reported for section EX3.

c) Statics Concept Inventory Results

To investigate the research question of whether the process problems affect student conceptual understanding, scores from the Statics Concept Inventory (SCI) were compared between sections. In addition to excluding records that contained zero on the final exam, excluding records that had zeroes on over half of the process problems further reduced the number of students who completed the SCI by two in EX3, bringing the total to 81 (58% of the total class). Figure 9 shows histograms of the SCI score percentage for each section; summary statistics are provided in Table 15.

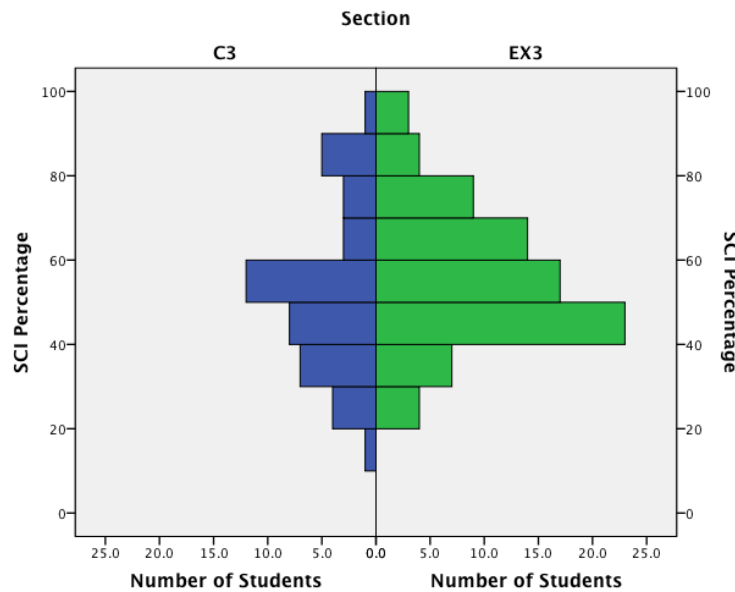


Fig. 9. Histograms of SCI Scores for Students in Sections C3 and EX3.

TABLE 15. SUMMARY STATISTICS OF SCI PERCENTAGE FOR STUDENTS IN SECTIONS C3 AND EX3.

Section	N	Median	Mean	SD
C3	48	51.85	53.6	18.894
EX3	81	51.85	55.5	16.527

Both histograms in Figure 9 appear to approximate a normal distribution, and mean score percentages reported in Table 15 do not appear to be largely different from one another. Results from the Shapiro-Wilk test confirm that the distribution of SCI score percentages in section C3 is normal ($W=0.962$, $df=44$, $p=0.157$), as is the distribution for EX3 ($W=0.975$, $df=81$, $p=0.144$). Results from the t-test confirm that the mean SCI score percentage is not statistically different between the two groups ($t=0.580$, $df=123$, $p=0.563$).

Finally, possible correlations between process problem grades and SCI scores were explored. An average process problem grade was calculated for students in the experimental section and correlated with their post-score on the SCI if available. Tests indicated no significant correlation between process problem average and scores on the post-test of the SCI.

d) Student Grades

To investigate how process problems affect student performance in statics, course grades on tests and the final exam were analyzed. Tests for normality were first conducted in a similar manner to that described previously, and the results indicated that at least one section had a non-normal distribution of scores for Test 1, Test 2, and the Final Exam. Distributions for Tests 3 and 4 were normal for both sections. Again, the parametric t-test was used to compare the mean scores between the two sections for items that were normally distributed; the non-parametric Mann-Whitney U test was used to compare distributions that did not meet assumptions of normality. The statistical test results for each item are shown in Table 16 below, along with summary statistics.

TABLE 16. SUMMARY STATISTICS AND STATISTICAL TEST RESULTS COMPARING STUDENT GRADES IN SECTIONS C3 AND EX3.

Item	Section	N	Median	Mean	SD	Test Statistic	df	p value
Test 1	C3	81	71	69.81	18.225	U=5331.5	--	.290
	EX3	121	73	72.89	18.185			
Test 2	C3	81	62	60.15	20.604	U=4980.0	--	.845
	EX3	121	63	61.52	20.594			
Test 3	C3	81	57	56.64	19.296	t=0.714	200	0.476
	EX3	121	60	58.58	18.626			
Test 4	C3	81	62	60.85	22.981	t=0.907	200	0.365
	EX3	121	63	63.72	21.343			
Final Exam	C3	81	70	69.57	18.204	U=5658.0	--	.062
	EX3	121	75	74.48	16.896			

As shown in the table above, the results from all tests indicate that no statistical differences exist between sections EX3 and C3 with regard to scores on tests and the final exam. Thus, there appears to be no differences in indicators of procedural knowledge between students that completed the process problems and those that did not.

e) Summary

In this implementation, students in the experimental section on average were not statistically different than students in the control section with regard their conceptual knowledge of statics content as measured by the SCI. This is despite the self-selection bias that appears to exist in the SCI data for section EX3, which may serve to overestimate the average SCI score for that section. Thus, the experimental group may actually have a slightly lower average SCI score compared to the control group, though this cannot be confirmed.

The experimental and control groups were not different with regard to measures of procedural knowledge (tests and final exam).

V. INTERPRETATION AND CONCLUSION

A. Review of the RQs

This study aimed to investigate the learning approaches taken by statics students with regard to conceptual and procedural knowledge development. It also examined how short, frequent written assignments called process problems might improve the conceptual knowledge of statics students. Specifically, the following research questions were presented for investigation:

RQ1. How do students approach learning in statics with regard to conceptual and procedural knowledge development? (qual)

RQ2. What is the interaction between the process problems and conceptual knowledge development? (mixed)

RQ2a. How do students utilize the process problems with regard to ways that may work to develop conceptual knowledge, particularly through reflection? (qual)

RQ2ai. Do different learning approaches influence the way that students utilize the process problem assignments? (qual)

RQ2b. To what degree do the process problems affect conceptual knowledge development? (quant)

The results presented in Chapter 4 will be summarized for each research question and followed by a discussion of the results. The discussion will situate the findings of this study within the context of related literature published since its onset, incorporating additional research threads that were not included in the literature review as needed to help explain the findings. Finally, the contributions of the study will be summarized and some directions for future work will be outlined.

B. Summary of Findings and Discussion of Findings

1) *RQ1: How do students approach learning in statics with regard to conceptual and procedural knowledge development? – Findings and Discussion*

Based on the review of current literature and previous studies related to statics, it was hypothesized that many statics students may adopt approaches primarily focusing on the development of procedural knowledge. It was not known to what degree students actively sought out conceptual knowledge or what means they used to do so. Thus, one goal of this study, linked to RQ1, was to explore this qualitatively through interviews with students.

a) RQ1 Findings

The results show that the participants in this study adopted a range of learning approaches, which were depicted along a continuum varying with regard to the type of knowledge most heavily emphasized by the student. On one end, procedure-centered students are those that engage in actions that develop procedural knowledge nearly exclusively. On the other end, concept-centered students are those that nearly exclusively develop conceptual knowledge. Balanced students, in the middle of the spectrum, engage in activities that place approximately equal emphasis on procedural and conceptual knowledge development. As noted previously, there were no students identified that placed a stronger emphasis on conceptual knowledge compared to procedural knowledge. Furthermore, eleven participants out of the thirty-two total could not be placed into a learning approach category due to limited information provided during their interview. Thus, the twenty-one participants that could be classified fell into one of four groups: procedure-centered (five participants), procedure-heavy (four participants), near-balanced (four participants), and balanced (eight participants).

All categorized participants engaged in activities that would work to develop procedural knowledge. Primary among these was practicing solution procedures by working assigned homework and, in some cases, other additional problems. Many students cited working problems as their most helpful learning resource, and many used their ability to solve new problems as an indicator of their understanding. As stated above, however, the participants varied in their reported engagement in activities that focus on conceptual knowledge development relative procedural knowledge development. Balanced and near-balanced students differed most from procedure-centered and procedure-heavy students in two primary areas: problem solving approaches and studying approaches.

With regard to problem solving during homework or other low-stakes practice, procedure-heavy and procedure-centered students tended to use their course resources to search for specific example procedures that could be applied to the given problem. These procedures often come from worked-out example problems from that section of the book or notes and are then “tested” on the new problem in a guess-and-check fashion. The focus of problem solving is often on getting a correct answer, after which students like Charles “just celebrate” rather than seek out an understanding of their solution process. On the other hand, more balanced students look more often in the content section of the book and try to understand how a general procedure can be applied to their particular problem. Thus, while they still use their course resources as tools to search for procedures, they more often seek out justification of why it is appropriate before attempting to apply the procedure to their problem. The focus of problem solving shifts

away from only getting a correct answer and more toward understanding why a solution works and connecting that with information found in course resources, with students like Kristen asking themselves “what are they actually doing?” and “how do I translate that back to what I’m being asked?”

The way that participants with procedure-centered and procedure-heavy learning approaches versus those with near-balanced and balanced approaches described their methods of studying is also different. This difference seems to arise at least in part due to their different problem solving approaches. As mentioned above, many students across the full range of identified learning approaches judged their level of understanding on their ability to solve problems. Studying for tests and exams therefore included a large focus on problem solving. However, the difference in studying approaches among procedure-centered and procedure-heavy versus near-balanced and balanced may best be described as a focus on problem quantity versus problem quality, respectively. Procedure-focused students approached studying from a perspective of problem quantity. The number of problems that they worked was seen by them as a key factor, and they judged their level of understanding more often on how many problems they had worked correctly. More balanced students, on the other hand, tended to approach studying from a perspective of problem quality. They worked fewer problems, focusing more often on those that appeared difficult, and judged their level of understanding more by their ability to understand why their correct solutions were successful. To do this, they often connected with relevant statics content knowledge and/or knowledge from a related course like Physics.

b) Discussion of RQ1 Findings

The finding that all students approached learning through actions that would develop procedural knowledge is potentially not surprising given the traditional focus of statics homework assignments and other assessments on judging students’ abilities to solve problems. Indeed, students like Alex from the LMAP institution seem to be influenced with regard to learning approach by assignments that are only checked for correct answers and allow for multiple attempts. Assessments like these may encourage students to preference procedures over concepts. On the other hand, assignments like the process problems may encourage students to focus more on concepts over procedures; this will be explored more in the sections below. The course instructor may also have an influence on how students perceive the relative importance of conceptual and procedural knowledge; comments from Ezra and Bill from the SPri institution seem to support this. Yet, the interviews provide evidence that other students from the same classes, interacting with the same instructor and given the same assignments, still took different approaches to learning. This was true across both of the institutional settings and three instructors included in these findings. Thus,

the findings from this study show that even when exposed to the same instructor, assignments, etc., students still adopt a range of learning approaches varying with regard to the relative emphasis that they place on conceptual knowledge development in relation to procedural knowledge development. Two major questions arise from this conclusion: (1) why do students adopt different learning approaches when exposed to the same instructional setting? and (2) is there a “best” or most effective approach for students to take? While neither of these questions can be answered fully here, some insights and anecdotal support will be explored below.

First is the question of why students adopt different learning approaches. The answer to this question necessarily involves an investigation of the motivations of students in statics in addition to consideration of the instructional influences discussed above. While this was not a goal of data collection for this study, participants nevertheless brought up some of these motivations during their interviews. Most often, students reported being influenced by older siblings or peers, who conveyed to them the importance of understanding statics content for use in follow-up courses. Some of the near-balanced and balanced students in particular used this as justification for spending more time on activities that develop conceptual knowledge. In addition, some repeat students discuss how their previous attempt at the course has prompted a change in their learning approach toward focusing more on concepts; Amy is one such example. However, it is perhaps worth noting also that it is not clear from the interviews if all students are necessarily intentional in their approach to learning. Some students either do not seem to be aware of how they approach learning or recognize that there may be other ways to go about it. Scott, another repeat student, notices a change in his understanding between his two course attempts, yet it is not clear if he has made a conscious decision to change his approach, saying only that going through the material again gave him a better grasp. Melissa recognizes that her learning approach, particularly with regard to studying, is not effective, but she seems unaware of how to make a change, saying simply, “I don’t know what else I can do to study.” Thus, students may adopt a particular learning approach in statics as a result of complex interactions among instructional and social influences as well as personal experiences and their own understanding of learning.

The second question asks: is there a “best” or most effective learning approach to take in statics? The answer to this obviously depends on what outcomes are desired, but in light of the assertions made in the opening chapters of this work, both procedural and conceptual knowledge are vital for future success in engineering. On the procedural knowledge side, studies of expertise highlight that practice is an essential component of progress toward becoming an expert (T. A. Litzinger et al., 2011). The ability to carry out procedures that have been practiced often with minimal

effort, known as automaticity, is a defining feature of experts (J. Bransford et al., 2003). Furthermore, it is a feature known to make them better able to engage in problem solving when compared to novices (Chi et al., 1981). Thus, practicing common procedures in statics, as done by all participants in this study, is an important and worthwhile activity needed to help students develop statics expertise. The question then becomes: aside from practice needed for procedural knowledge, how can instructors get students to also develop conceptual knowledge? Math education researchers argue that procedural and conceptual knowledge are interrelated (Rittle-Johnson & Alibali, 1999; Sfard, 1991). The idea that the two types of knowledge lie on a continuum reflects an inability to ever fully separate one from the other (Rittle-Johnson & Alibali, 1999). That is, although knowledge may be identified as “more procedural” or “more conceptual” in nature, most problem-solving tasks elicit knowledge that inevitably contains elements of both. Moreover, some empirical evidence suggests that it doesn’t matter which is learned first (Rittle-Johnson & Alibali, 1999). If this is true, then practice should result first in the development of procedural knowledge followed closely by the development of conceptual knowledge.

However, this does not seem to be the case in statics, at least as suggested by previous observations of poor conceptual understanding even among students who pass the course and thus have some level of proficiency in carrying out statics procedures (e.g., Danielson, 2004; Passmore et al., 2010). One possible explanation for the disconnect between procedural and conceptual knowledge may be that statics courses—and engineering science courses more generally—involve the combination of procedural and conceptual knowledge originating from different domains. Specifically, procedural knowledge from mathematics is used in conjunction with conceptual knowledge from science (particularly physics in the case of statics), a process that continues with increasing complexity in engineering science courses. Mathematics education research involving conceptual and procedural knowledge, on the other hand, typically involves studying both types of knowledge within a single domain. Thus, while students in statics who focus primarily on procedure may eventually develop greater mathematic conceptual knowledge related to those procedures, they may still fail to connect with the necessary conceptual knowledge from science. This mixing of domain knowledge may be an important factor that contributes to statics as a “threshold concept” course for engineering (J. H. F. Meyer & Land, 2005). It may also advocate for the use of learning approaches that balance conceptual and procedural knowledge in statics.

2) *RQ2: What is the interaction between the process problems and conceptual knowledge development?* –

Findings and Discussion

At the onset of this study, it was hypothesized that the process problems might be used as a formal tool to help students develop conceptual knowledge through reflection. Specifically, if the process problems did elicit reflective thought, and reflection is a mechanism for conceptual knowledge development, then it is reasonable to infer that students engaging in the act of completing the process problems may experience greater conceptual knowledge gains than those not engaging with the process problems. Thus, a second goal of the study, linked to RQ2, was to investigate this using a mixed-methods approach. The first part of this, RQ2a, was to search for evidence of reflection as a result of completing the process problems. This again was approached qualitatively through interviews with students. A sub-goal of RQ2a was to search for information about whether a student's learning approach influenced the type(s) or reflection that were undertaken when completing the process problems. This was approached by combining the two previous qualitative data sets. Finally, the second part of RQ2 was to search for evidence of greater conceptual knowledge possessed by students who completed the process problems compared to those who did not as stated in RQ2b. This was done quantitatively in a quasi-experimental setup and used the statics concept inventory as a tool to measure the conceptual knowledge of statics students on a large scale upon completion of the course. Here, the findings from RQ2a and RQ2b will be revisited and then interpreted together.

a) RQ2a: How do students utilize the process problems with regard to ways that may work to develop conceptual knowledge, particularly through reflection?

The results presented in Chapter 4 show that the process problems did prompt many participants to engage in reflective activities, which were categorized into four groups: self-explanation, checking understanding, organizing solution process, and generalizing solution process. In total, 26 of the 32 participants were identified as discussing at least one type of reflection prompted by the process problems. Of the remaining six, three participants were classified as engaging in little to no reflection, and another three did not provide enough information during their interviews to make a determination. Self-explanation and checking understanding were the two most common types of reflection, being reported by 15 and 14 participants, respectively. Of these, six participants discussed both types of reflection. Fewer participants reported using the process problems to organize and generalize their solution process (6 and 4 participants, respectively).

b) RQ2ai: Do different learning approaches influence the way that students utilize the process problem assignments?

Self-explanation and checking understanding, the most common types of reflection discussed by participants, were described by students from the entire range of identified learning approaches and did not seem to favor either the more balanced students or students focused more on procedure. In fact, many students whose learning approach could not be identified also discussed these as the type of reflection that they did or would engage in while completing the process problems. Self-explanation and checking understanding thus may be more accessible types of reflection that students from a wide range of learning approaches can engage in. On the other hand, organizing and generalizing a solution process were types of reflection reported less frequently; they were also discussed almost exclusively by students from the near-balanced and balanced learning approach groups with Ralph, whose learning approach could not be identified, being the only exception. Interestingly, control group participants predicted that they would use the process problems in similar ways as the experimental group participants of the same learning approach. Self-explanation and checking understanding were among the most common expected types of reflection reported although there were instances of control group students saying that they would also use the process problems to organize and generalize their solution process. Again, these students were identified as having near-balanced and balanced learning approaches. Thus, organizing and generalizing solution process may be types of reflection more accessible to, or preferred by, students more equally focused on procedural and conceptual knowledge development. These conjectures cannot be supported conclusively from the data collected for this study, but some reasons supporting these possible explanations will be explored more fully in the discussion section. Overall, though, these results do provide some evidence that learning approach might play a role in determining how participants utilize the process problems.

c) RQ2b: To what degree do the process problems affect conceptual knowledge development?

The analyses of quantitative data collected to answer RQ2b yielded mixed results. During the pilot implementation, the experimental group who completed the process problems scored higher on average than the control group on the end of term SCI. This difference was statistically significant and corresponded to a medium-large effect size. Substantively, the difference between groups was approximately three questions from the 27-item inventory, with a 95% confidence interval ranging from 1 to 5 questions. However, these results were not replicated during the Fall 2011 implementation, for which the scores on the end of term SCI were not statistically different

between the control and experimental groups. The similarity in scores was present despite a possible bias of stronger students in the experimental section self-selecting to take the SCI. During both implementations, average scores on the process problems did not correlate with scores on the SCI, nor was there a difference in test and exam grades between the two sections.

d) Discussion of RQ2 Findings

The findings from RQ2a and RQ2b together do not support a definitive conclusion on the ability of the process problems to improve the conceptual knowledge of students beyond gains normally provided by the course alone. On one hand, the qualitative findings from RQ2a do provide evidence that the process problems did in fact prompt reflective activity for a wide range of students, particularly with regard to self-explanation and checking understanding. These are actions previously tied to conceptual knowledge development by relating different symbol systems (Hiebert & Lefevre, 1986) and providing justification for steps of a solution process (Chi, Bassok, Lewis, Reimann, & Glaser, 1989). More recent studies in math education also empirically support that higher levels of conceptual knowledge can result from self-explanation prompts when compared to simply going through more practice, even when controlling for time on task (McEldoon, Durkin, & Rittle-Johnson, 2013). This would provide support for assignments like the process problems from this study. Other studies suggest that concept-focused instruction might be a better option for improved conceptual knowledge beyond self-explanation prompts (Matthews & Rittle-Johnson, 2009). However, encouraging widespread adoption of research-based educational innovations among engineering faculty remains a challenging process (Borrego, Froyd, & Hall, 2010). Thus, assignments like the process problems may provide a simple way of supporting conceptual knowledge development in a statics classroom without requiring changes to instruction, therefore increasing adoption.

Generalizing a solution process was an activity reported by some of the near-balanced and balanced students. It is difficult to tell if their focus on conceptual knowledge development was the driver for their engagement in this type of reflection or if their conceptual knowledge is what made it possible. Likely, it is due in part to both, but more research is needed to answer this more fully. Regardless, generalizing a solution process is an activity that is likely to promote transfer to other problems, which would in turn improve the ability of students to become more adaptive problem solvers.

Despite the generally positive qualitative findings, the quantitative results of this study make it unclear if these intended benefits to conceptual knowledge due to reflection were realized in practice. While the Spring 2011 implementation showed promise for the process problems as a way to measurably improve the conceptual knowledge of statics students, the Fall 2011 results did not support this conclusion. Overall, the lack of true random assignment and random sampling threatens the validity of the quantitative findings. The non-random assignment of participants into experimental and control groups is a limitation that was attempted to be partially addressed through the alternating of course sections assigned to the intervention between the Spring 2011 and Fall 2011 implementations at LMAP. In addition, the effect of non-random sampling for each implementation was explored through the self-selection bias analysis. However, the widespread lack of students who chose to take the SCI during both implementations greatly limits the usefulness of the data collected.

C. Conclusions and Contributions

This study contributes to the field of engineering education research in two major areas and offers directions for future work related to the study of conceptual knowledge in statics.

First, it adds to the dialogue surrounding the problem of conceptual understanding in statics among the engineering education community. Many efforts have been made previously by engineering education researchers to document statics misconceptions (e.g. PS Steif & Dollár, 2005), improve pedagogical techniques (e.g. P. S. Steif et al., 2010), and measure the conceptual knowledge of students entering and leaving the course (e.g. P. S. Steif & J. A. Dantzer, 2005). These initial efforts provided a foundation for further study of methods and tools for improving conceptual knowledge in statics by an expanding pool of researchers and practitioners. Even since the inception of this study, other researchers have implemented computer visualization tools (Powell, Richards, Jensen, & Brown, 2014) and a mixture of peer learning, in-class problem solving, and self-assessment (Hargrove-Leak, 2013) into their courses to improve conceptual understanding. A multi-level, expert-generated concept map that allows novices to see the conceptual links among related course content without overloading their cognitive resources has been developed (Moore, Pierce, & Williams, 2012; Moore, Williams, North, & Johri, 2013). The statics concept inventory (SCI, or CATS), a common means of monitoring statics conceptual knowledge, has been translated for use with native Spanish-speaking students (Garca, Nieves, Pacheco, Marn, & Santiago-Romin, 2012) and investigated for its appropriateness as a formative assessment tool that can inform targeted instruction (Denick, Santiago-Romn, Pellegrino, Streveler, & DiBello, 2013; Denick, Santiago-Romn, Streveler, & Barrett, 2012). One study even uses a

writing intervention similar to the one used here, though employing different reflection prompts (Goldberg, Rich, & Masnick, 2014). In short, there seems to be a growing interest in improving conceptual knowledge among students in statics.

Joining in this effort, this study highlights the role that students play by documenting different ways that they approach learning in the course, even when exposed to the same instructional conditions. Furthermore, it shows that the learning approach of students may influence the way that they interact with course assignments intended to improve conceptual knowledge. It also brings in theoretical frameworks from mathematics education that might be used to help explain the problems facing statics students. At the least, it gives engineering education researchers and practitioners additional ways of thinking about the way that we educate and evaluate our students. As noted in the recent *Cambridge Handbook of Engineering Education Research*, a “shared understanding of the differences between procedural and conceptual knowledge would facilitate discussions of the role of undergraduate education in preparing engineers” (R. Streveler, Brown, Herman, & Montfort, 2014, p. 97). The findings here begin that process of working toward a shared understanding.

Second, this study contributes to the writing-to-learn community, whose research findings have not been widely incorporated into the engineering (and science) education communities (Reynolds, Thaiss, Katkin, & Thompson, 2012). By building on the work by Hanson and Williams (2008), who originally developed this style of written problem for use in smaller classrooms to improve the self-assessment and communication skills of their students, this study demonstrates the feasibility of implementing writing assignments with graded feedback in large engineering science courses. The use of engineering graduate teaching assistants at LMAP showed that the assignment scales to accommodate larger settings typical of many introductory courses at research universities while still providing consistent feedback to students. This is a critical challenge facing writing-to-learn advocates in engineering education (Troy, Essig, Jesiek, Boyd, & Trellinger, 2014). This study also provides evidence of the process problem prompting students to engage in reflective actions that they admittedly otherwise would not. While the quantitative data was not able to neither corroborate nor quantify an improvement of conceptual knowledge among students who completed the process problems, it still illustrates how a validated instrument could be used to assess conceptual knowledge gains as a result of writing on a large scale. Other studies involving writing-to-learn in engineering have typically assessed the intervention’s effect using end of course grades (e.g., Goldberg et al., 2014; Hanson & Williams, 2008). Using concept inventories to isolate conceptual knowledge for assessment may help more accurately evaluate the usefulness

of writing in promoting conceptual knowledge development. This can help to further validate the effects of writing-to-learn interventions in engineering and, if warranted, provide evidence for their adoption.

D. Limitations and Future Work

A large limitation of this study arises from the amount of missing SCI data as mentioned in previous sections. This influence of this missing data was explored on a rudimentary level in Chapter 4 through the self-selection bias analysis. Further work to address this limitation may involve the use of imputation techniques (Rubin, 1987) to give a more accurate estimate of the true SCI mean scores in each section. This would provide a more complete picture of how the written process problems affected the conceptual understanding of students in the participating experimental sections.

Another possible limitation of this study involves the use of interviewing to elicit the ways that students interacted with the process problems. By their very nature, the interview questions prompt a participant to reflect on previous actions and the cognitive processes evoked when originally completing a process problem. Thus, since answering the interview question requires reflection in itself, it is difficult to discern between reflections that actually occurred spontaneously while writing the process problems and the reflective action prompted by the interview. Future work to investigate this possible limitation may include more direct observational data to further validate or refute the findings reported in this study. Observation at the time of problem completion would be one way to approach this; yet, another approach may involve an analysis of the process problems themselves. For example, cataloging instances of students supporting their procedures with appropriate reasoning may further evidence the checking understanding type of reflection that participants purported undergoing when asked in the interview. Other types of reflection that were reported, like a organizing solution process, would be more difficult to corroborate using this approach since the mathematical solution for the problem would likely be needed as well. However, since the process problem artifacts have already been collected during this study, performing an analysis of the existing problems for further evidence would be a logical next step.

Given the interactions between learning approach and types of reflection reported in the findings of this study, the data collected here might in the future also be constructively analyzed and interpreted using a theoretical framework explicitly incorporating metacognition and self-regulated learning, which derive from the seminal works of John Flavell (1979) and Ann Brown (1987). Using Flavell's original framework, for example, students engaging in

checking understanding may be viewed as having “metacognitive experiences” (i.e. Flavell, 1979) by which they realize that their knowledge of a topic is insufficient or incomplete. This would then prompt the use of either a cognitive strategy to correct the knowledge deficiency or a metacognitive strategy to further assess their level of understanding of the topic (Flavell, 1979). Of course, if the result of the self-assessment determines that their knowledge is insufficient, a student may still have an opportunity to employ a cognitive strategy. Employing a cognitive strategy would work to develop conceptual knowledge, from which we might expect to see an increase in conceptual knowledge among students completing the process problems as documented in this work. Similarly, first employing a metacognitive strategy may help to build metacognitive knowledge needed to perform knowledge assessments. This might explain the improved self-assessment skills documented by Hanson and Williams in their original study involving the process problems. Thus, the process problems should help to develop elements of self-regulation, which involves “the cognitive and metacognitive regulatory processes used by individuals to plan, enact, and sustain their desired courses of action” (Volet, Vauras, & Salonen, 2009, p. 216). Yet, the ability of the process problems to promote this development in students may be dependent on their learning approach. Future studies investigating improvements in metacognitive knowledge and self-regulation as a result of the process problems might employ observational data as to avoid the same problems with interviewing discussed above. Observation protocols have been used to code for instances of metacognition and self-regulation in children (Whitebread et al., 2009) and recently have been adapted for use with engineering undergraduates (McCord, 2014). to improve their conceptual knowledge.

The findings from this study also identify a need for further work on the classification and documentation of learning approaches that students take in statics and other engineering science courses. If learning approaches could be reliably determined on a large scale, such as through the use of a survey instrument, then quantitative answers to questions RQ1 and RQ2ai could be explored. Knowing the learning approaches of statics students on a large scale may also help to develop interventions and curricula that could encourage greater development of conceptual knowledge. A related area for further investigation concerns how students develop their approach to learning. As mentioned previously, one might expect that a range of motivational and other factors may play a role in the learning approach adopted by students in statics. Studies documenting and exploring these factors may be of particular interest. They may help to discover if learning approaches change over time, and if so, what factors influence those

changes. The results could lead to development of interventions designed to alter the learning approach of students, leading to better learning outcomes.

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APPENDICES

Appendix A1. Process Problem Guidelines Spring 2011 (Pilot)

Objectives for Process Problem Assignments

Like any of the problems assigned in this course, the main goal of having you work through these “process problems” is to help you in your goal of understanding Statics (and Engineering in general). Much of a typical engineering course is taught and practiced through numbers and equations, and for good reason; these are the tools that we commonly use to explain engineering phenomena. However, writing in words about these engineering topics may also help improve your ability to learn about them. You may have similarly experienced this when studying with friends; many students report that explaining a topic in words to someone else actually helps him/herself understand the material better. These problems are designed to provide you an opportunity to go through the same process in a more structured way.

Instructions to Complete Process Problems

For the specified problem, describe in words the steps followed in order to set up and solve the problem in such a way that someone else in the class should be able to understand. Begin by stating the objective(s) of the problem. Please limit your response to three-fourths of a page typed, either single-spaced in Times New Roman 12 or 1.15-spaced in Calibri 11 (Word 2007/2010 default).

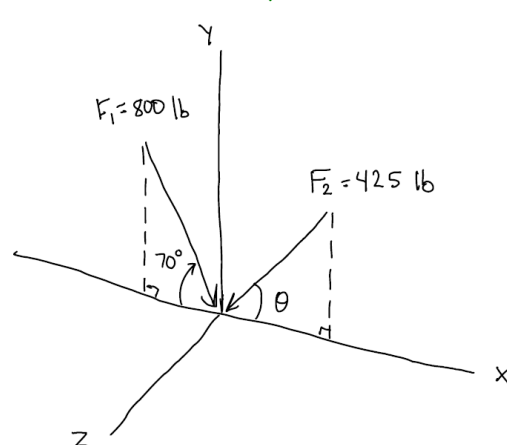
You may choose to format your response in either paragraph form or as a list of steps, but in either case, use complete sentences. Each sentence of your solution should be understandable without relying on another sentence. If you are unsure as to whether a certain process or term needs more description, err on the side of caution and include it in your response (while maintaining the three-quarter page limit). However, the written procedure should be focused on the Statics concepts and processes necessary for solving the problem. Your written procedure should *not* focus on the particular numbers associated with the problem. Use **boldface** type to indicate vectors and *italics* to indicate scalars.

It is strongly recommended that you first work out the specified problem on paper and logically organize your solution process before beginning this written assignment. Your goal is to make your instructions as simple to understand as possible while still being complete. Since your figures will not be included as part of your written response, be sure to describe any variable names that you create. For problems involving equilibrium, be sure to also include information that indicates which body(ies) you have isolated for your free body diagram(s) and what forces/moments you have included.

Your written procedure will be graded based on the following criteria:

- Has the student provided sufficient detail that another beginning Statics student could reproduce the approach to the solution?
- Has the student demonstrated an understanding of what is being done in the solution process?
- Is the description written such that I can understand what the student means?
- Is the description focused on the *approach* to the solution of this problem, not the specific numbers of the solution?

Appendix A2. Example Problem Solution and Corresponding Process Problem

Problem #	Date	Last Name, First Name
 <p style="margin-left: 40px;"> $F_1 = 800 \text{ lb}$ $F_2 = 425 \text{ lb}$ </p> <p style="margin-left: 40px;"> Find θ such that the resultant of the two forces is vertical. Determine the magnitude R of the resultant. </p> <p style="margin-left: 40px;"> $\vec{F}_1 = \{800 \cos 70^\circ \hat{i} - 800 \sin 70^\circ \hat{j}\} \text{ lb}$ $\vec{F}_2 = \{-425 \cos \theta \hat{i} - 425 \sin \theta \hat{j}\} \text{ lb}$ </p> <p style="margin-left: 40px;"> The resultant force is given by $\vec{R} = \{(800 \cos 70^\circ - 425 \cos \theta) \hat{i} + (-800 \sin 70^\circ - 425 \sin \theta) \hat{j}\} \text{ lb}$ For the resultant to be vertical, the x-component must be zero. </p> <p style="margin-left: 40px;"> $800 \cos 70^\circ - 425 \cos \theta = 0 \Rightarrow \theta = 49.9^\circ$ </p> <p style="margin-left: 40px;"> Plugging this value of θ into \vec{R}, we find $\vec{R} = -1076.96 \hat{j} \text{ lb}$ The magnitude of \vec{R} is $R = 1077 \text{ lb}$ </p>		1/1

The first objective of this problem is to determine the angle θ that the force \mathbf{F}_2 makes with the positive x-axis such that the resultant force produced by the forces \mathbf{F}_1 and \mathbf{F}_2 is vertical. The second objective is to determine the magnitude of the resultant force.

The first step is to express each of the two forces in component form. To decompose force \mathbf{F}_1 , extend a line vertically downward from the tail of the vector so that the line forms a right angle with the negative x-axis. Then, using right triangle trigonometry, find the magnitudes of the x- and y-scalar components of \mathbf{F}_1 . The x-component of \mathbf{F}_1 should be positive, and the y-component should be negative. Decompose \mathbf{F}_2 in a similar manner, this time extending a vertical line from the tail of \mathbf{F}_2 to form a right angle with the positive x-axis. Express the x- and y-components of \mathbf{F}_2 in terms of the unknown angle θ . Both the x- and y-components of \mathbf{F}_2 should be negative.

Calculate the resultant force, \mathbf{R} , by adding the two forces \mathbf{F}_1 and \mathbf{F}_2 . Add the x-components of \mathbf{F}_1 and \mathbf{F}_2 to form an expression for x-component of \mathbf{R} . Next, add the y-components of \mathbf{F}_1 and \mathbf{F}_2 to form an expression for the y-component of \mathbf{R} . If the resultant is to be vertical, then \mathbf{R} must not have an x-component. Set the expression for the x-component of \mathbf{R} equal to zero to solve for θ .

Using the value of θ found previously, evaluate the resultant vector \mathbf{R} . Calculate the magnitude of \mathbf{R} by taking the square root of the sum the squares of each of its components. The x-component of \mathbf{R} should be zero, and the magnitude of \mathbf{R} should be a positive value.

Appendix A3. Process Problem Grading Rubric Spring 2011 (Pilot)

Criteria	Full Credit (2 pts)	Partial Credit (1 pt)	No Credit (0 pts)
Has the student provided sufficient detail that another beginning Statics student could reproduce the approach to the solution?	<p>Identify sequence by which unknowns are being found.</p> <p>Variables used in each equation are identified.</p> <p>Body or particle chosen for FBD is identified (if applicable).</p>	<p>One necessary step is missing or steps are slightly out of order.</p> <p>Variables used are not identified in one equation.</p> <p>Body or particle for FBD not clearly identified.</p>	<p>More than one necessary steps are missing or greatly unordered.</p> <p>Variables used are not identified for multiple equations.</p>
Has the student demonstrated an understanding of what is being done in the solution process?	<p>Approach described is fundamentally sound.</p> <p>Each equation used is described in words, not with algebra.</p>	<p>One error in the approach or distracting extraneous information.</p> <p>One equation described algebraically.</p>	<p>Multiple errors in approach.</p> <p>Multiple equations described algebraically.</p>
Is the description written such that I can understand what the student means?	<p>Description begins with the objective of the problem.</p> <p>Description no longer than $\frac{3}{4}$ page typed, single-spaced.</p> <p>Pronouns have clear meanings (each sentence is easily understandable).</p>	<p>Description does not begin with the objective of the problem.</p> <p>Description more than $\frac{3}{4}$ page, but less than 1 page.</p> <p>One or two sentences are not clear.</p>	<p>Description more than one full page typed.</p> <p>More than two sentences are not clear.</p>
Is the description focused on the <i>approach</i> to the solution of this problem, not the specific numbers of the solution?	<p>No problem-specific quantities are used in the description.</p> <p>Details are provided about solving this particular problem.</p>	<p>One problem-specific quantity is provided in the description.</p> <p>Description is about how to solve this type of problem in general.</p>	<p>More than one problem-specific quantity is provided in the description.</p>

Objectives for Process Problem Assignments

Like any of the problems assigned in this course, the main goal of having you work through these “process problems” is to help you in your goal of understanding Statics (and Engineering in general). Much of a typical engineering course is taught and practiced through numbers and equations, and for good reason: these are the tools that we commonly use to explain engineering phenomena. However, writing in words about these engineering topics may also help improve your ability to learn about them. You may have similarly experienced this when studying with friends; many students report that explaining a topic in words to someone else actually helps him/herself understand the material better. These problems are designed to provide you an opportunity to go through the same process in a more structured way.

Instructions to Complete Process Problems

Your written procedure will be graded based on the following criteria:

- **Has the student provided sufficient detail that another beginning Statics student could reproduce the approach to the solution?** For the specified problem, describe in words the steps you followed in order to set up and solve the problem in such a way that someone else in the class should be able to understand. If you are unsure as to whether a certain process or term needs more description, err on the side of caution and include it in your response (while maintaining the three-quarter page limit). Since your figures will not be included as part of your written response, be sure to describe any variable names that you create. For problems involving equilibrium, be sure to also include information that indicates which body(ies) you have isolated for your free body diagram(s) and what forces/moments you have included.
- **Has the student demonstrated an understanding of what is being done in the solution process?** It is strongly recommended that you first work out the specified problem on paper and logically organize your solution process before beginning this written assignment. Check all steps in your approach for accuracy.
- **Is the description written so that an expert (TA or instructor) can understand what the student means?** Your goal is to make your instructions as simple to understand as possible while still being complete. Begin by stating the objective(s) of the problem (what your solution process will result in). You may choose to format your response in either paragraph form or as a list of steps, but in either case, use complete sentences. Each sentence of your solution should be understandable without relying on another sentence.
- **Is the description focused on the *approach* to the solution of this problem, not the specific numbers of the solution?** The written procedure should be focused on the Statics concepts and processes necessary for solving the problem. Your written procedure should *not* include the particular numbers associated with the problem.
- **Is the assignment formatted according to guidelines given?** Please limit your response to three-fourths of a page typed, either single-spaced in Times New Roman 12 or 1.15-spaced in Calibri 11 (Word 2007/2010 default). Use **boldface** type to indicate vectors and *italics* to indicate scalars.

Appendix A5. Revised Process Problem Grading Rubric (Fall 2011 onward)

Criteria	Full Credit (2 pts)	Partial Credit (1 pt)	No Credit (0 pts)
Has the student provided sufficient detail that another beginning Statics student could reproduce the approach to the solution?	Identify sequence by which unknowns are being found. Variables used in each equation are identified. Body or particle chosen for FBD is identified (if applicable).	One necessary step is missing or steps are slightly out of order. Variables used are not identified in one equation. Body or particle for FBD not clearly identified.	More than one necessary step is missing or greatly unordered. Variables used are not identified for multiple equations.
Has the student demonstrated an understanding of what is being done in the solution process?	Approach described is fundamentally sound. Each equation used is described in words, not with algebra.	One error in the approach or distracting extraneous information. One equation described algebraically.	Multiple errors in approach. Multiple equations described algebraically.
Is the description written such that an expert can understand what the student means?	Description begins with the objective(s) of the problem. Pronouns have clear meanings (each sentence is easily understandable).	Description does not begin with the objective of the problem. One or two sentences are not clear.	More than two sentences are not clear.
Is the description focused on the <i>approach</i> to the solution of this problem, not the specific numbers of the solution?	No problem-specific quantities are used in the description. Details are provided about solving this particular problem.	One problem-specific quantity is provided in the description. Description is about how to solve this type of problem in general.	More than one problem-specific quantity is provided in the description.
Is the assignment formatted according to guidelines given?	Description no longer than $\frac{3}{4}$ page typed using font size and paragraph spacing indicated. Vectors are boldfaced, scalars are italicized. No figures are present.	Description more than $\frac{3}{4}$ page, but less than 1 page. One or two vectors/scalars are not properly formatted.	Description more than one full page typed. More than two vectors/scalars not properly formatted. One or more figures are present.

Appendix B1. Interview Protocol for Participants in Experimental Sections Spring 2011 (Pilot)

1. Tell me about your experience in Statics this semester.
 - Anything else?
 - Tell me more about...
 - Elaborate on that some...
2. What do you do to try to learn statics beyond going to class?
 - Thinking about the things you mentioned, along with the actual lecture, which do you feel is most helpful in learning the material?
 - Why?
3. Next I'd like you to think about the way that you usually go about doing your homework. If you have a normal routine, describe what it is like. If you don't have a normal routine, what varies from assignment to assignment?
4. What do you feel is the most difficult concept that is covered in statics? Why?
5. Some people describe statics as being a "critical concept" course, or a "lightbulb" course. Why might you think people refer to it as such?
 - What do most students say about the course?

Next, I would like to talk to you some about the process problems that you had as part of your homework this semester.

6. Tell me about your experience with the process problems this semester.
7. Describe how you usually go about completing a process problem.
8. If I were to tell you that the process problems actually improved the amount that you and your classmates learned during the semester, what would you say?
 - Are there any reasons that you can think of why that might be true?
9. What if I were to tell you that the process problems had no effect on your learning this semester?
 - Are there any reasons that you can think of why that might be true?
10. If the statics instructors decided to use the process problem assignments again, what if anything do you think should be changed?
 - Can you go into any more detail about that?
 - What are some of the features if any that you liked?

Next, I want you to take a look at this problem. Read over the problem statement and the given figure, and give me your initial thoughts about them.

Next, go through and begin to solve the problem. You do not need to actually solve it, but at least set it up. As you work through it, say out loud any thoughts that pass through your mind, no matter how trivial. In essence, I want you to continuously let me know what is going on in your mind as you work through the problem.

(be sure to remind them to say what they are thinking if they are not doing so)

11. Follow-up questions:
 - Why did you...? (probe them about the decisions they made, especially if they were incorrect or seemed like guesses)
 - Is there a method or process that you are using to solve this problem?
 - To you, what is a free-body diagram?
 - What are reactions?
 - If moments calculated by inspection:
 - Why could you simply look at the figure and calculate the resulting moment at point A for each force?
 - How would this problem be different if the forces were not directed along the coordinate directions?
 - If moments calculated by cross product:
 - Why did you choose to use the cross product to find the moments at A?
 - Was it completely necessary in this case? In what case would it be?
 - Would you call this a difficult statics problem? Why or why not? How could it have been made easier? Harder?

Appendix B2. Interview Protocol for Participants in Control Section Spring 2011 (Pilot)

1. Tell me about your experience in Statics this semester.
 - Anything else?
 - Tell me more about...
 - Elaborate on that some...
2. What do you do to try to learn statics beyond going to class?
 - Thinking about the things you mentioned, along with the actual lecture, which do you feel is most helpful in learning the material?
 - Why?
3. Next I'd like you to think about the way that you usually go about doing your homework. If you have a normal routine, describe what it is like. If you don't have a normal routine, what varies from assignment to assignment?
4. What do you feel is the most difficult concept that is covered in statics? Why?
5. Some people describe statics as being a "critical concept" course, or a "lightbulb" course. Why might you think people refer to it as such?
 - What do most students say about the course?

This semester, some sections of statics participated in an experimental study that involved completing "process problems" for homework. Have you heard about these problems?

6. If yes, tell me what you have heard about them. If no, the problems were typed, essay-style problems in which students explained their process for solving a particular homework problem. The description was required to be words only, no equations or numbers.
7. What are your thoughts about these types of problems if they had been assigned to you?
 - Do you think you would have had trouble completing this type of problem? Why or why not?
 - Why do you think they might be helpful for students in statics?
 - Why might they not be helpful?

Next, I want you to take a look at this problem. Read over the problem statement and the given figure, and give me your initial thoughts about them.

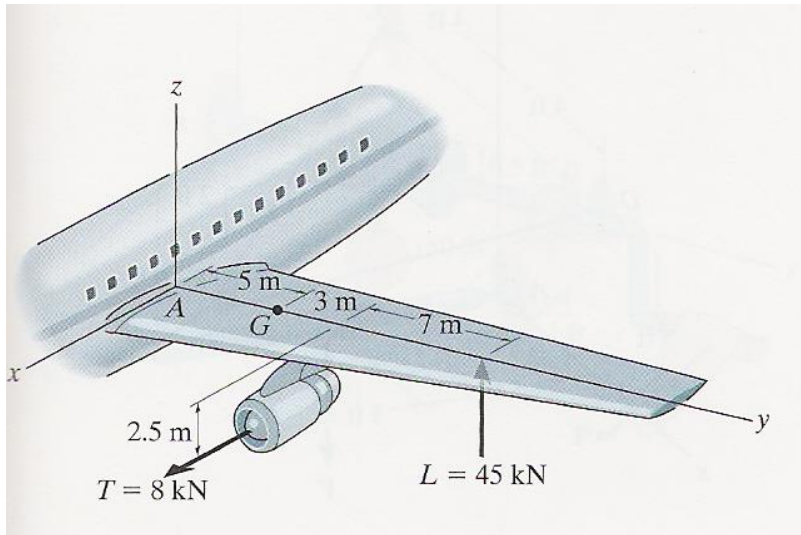
Next, go through and begin to solve the problem. You do not need to actually solve it, but at least set it up. As you work through it, say out loud any thoughts that pass through your mind, no matter how trivial. In essence, I want you to continuously let me know what is going on in your mind as you work through the problem.

(be sure to remind them to say what they are thinking if they are not doing so)

8. Follow-up questions:
 - Why did you...? (probe them about the decisions they made, especially if they were incorrect or seemed like guesses)
 - Is there a method or process that you are using to solve this problem?
 - To you, what is a free-body diagram?
 - What are reactions?
 - If moments calculated by inspection:
 - Why could you simply look at the figure and calculate the resulting moment at point A for each force?
 - How would this problem be different if the forces were not directed along the coordinate directions?
 - If moments calculated by cross product:
 - Why did you choose to use the cross product to find the moments at A?
 - Was it completely necessary in this case? In what case would it be?
 - Would you call this a difficult statics problem? Why or why not? How could it have been made easier? Harder?

Appendix B3. Think-aloud Handout for Interview Participants

The wing of the jet aircraft is subjected to a thrust of $T = 8 \text{ kN}$ from its engine and the resultant lift force $L = 45 \text{ kN}$. If the mass of the wing is 2100 kg and the mass center is at G , determine the reactions where the wing is fixed to the fuselage at A .



Appendix B4. Interview Protocol for Participants in Experimental Sections (Fall 2011 onward)

1. Tell me about your experience in Statics this semester.
 - Anything else?
 - Tell me more about...
 - Elaborate on that some...
2. What do you do to try to learn statics beyond going to class?
 - Thinking about the things you mentioned, along with the actual lecture, which do you feel is most helpful in learning the material?
 - Why?
3. Next I'd like you to think about the way that you usually go about doing your homework. If you have a normal routine, describe what it is like. If you don't have a normal routine, what varies from assignment to assignment?
4. What would you say are the major concepts covered in Statics?
 - What do you feel is the most difficult concept that is covered in statics? Why?
5. Some people describe statics as being a "critical concept" course, or a "lightbulb" course. Why might you think people refer to it as such?
 - What do most students say about the course?

Next, I would like to talk to you some about the process problems that you had as part of your homework this semester.

6. Tell me about your experience with the process problems this semester.
7. Describe how you usually go about completing a process problem.
 - Do you feel that you are a good writer?
 - What type of writing would you consider these problems to be, and is this type of writing useful to you as an engineering student?
8. If I were to tell you that the process problems actually improved the amount that you and your classmates learned during the semester, what would you say?
 - Are there any reasons that you can think of why that might be true?
9. What if I were to tell you that the process problems had no effect on your learning this semester?
 - Are there any reasons that you can think of why that might be true?
10. If the statics instructors decided to use the process problem assignments again, what if anything do you think should be changed?
 - Can you go into any more detail about that?
 - What are some of the features if any that you liked?

(Thank you. You are doing great.) Next, I want you to take a look at this problem. Read over the problem statement and the given figure, and give me your initial thoughts about them.

Next, go through and begin to solve the problem. You do not need to actually solve it, but at least set it up. As you work through it, say out loud any thoughts that pass through your mind, no matter how trivial. In essence, I want you to continuously let me know what is going on in your mind as you work through the problem.

(be sure to remind them to say what they are thinking if they are not doing so)

11. Follow-up questions:
 - Why did you...? (probe them about the decisions they made, especially if they were incorrect or seemed like guesses)
 - Is there a method or process that you are using to solve this problem?
 - To you, what is a free-body diagram?
 - What are reactions?
 - If moments calculated by inspection:
 - Why could you simply look at the figure and calculate the resulting moment at point A for each force?
 - How would this problem be different if the forces were not directed along the coordinate directions?
 - If moments calculated by cross product:
 - Why did you choose to use the cross product to find the moments at A?
 - Was it completely necessary in this case? In what case would it be?
 - Would you call this a difficult statics problem? Why or why not? How could it have been made easier? Harder?

Appendix B5. Interview Protocol for Participants in Control Sections (Fall 2011 onward)

1. Tell me about your experience in Statics this semester.
 - Anything else?
 - Tell me more about...
 - Elaborate on that some...
2. What do you do to try to learn statics beyond going to class?
 - Thinking about the things you mentioned, along with the actual lecture, which do you feel is most helpful in learning the material?
 - Why?
3. Next I'd like you to think about the way that you usually go about doing your homework. If you have a normal routine, describe what it is like. If you don't have a normal routine, what varies from assignment to assignment?
4. What would you say are the major concepts covered in Statics?
 - What do you feel is the most difficult concept that is covered in statics? Why?
5. Some people describe statics as being a "critical concept" course, or a "lightbulb" course. Why might you think people refer to it as such?
 - What do most students say about the course?

This semester, some sections of statics participated in an experimental study that involved completing "process problems" for homework. Have you heard about these problems?

6. If yes, tell me what you have heard about them. If no, the problems were typed, essay-style problems in which students explained their process for solving a particular homework problem. The description was required to be words only, no equations or numbers.
7. What are your thoughts about these types of problems if they had been assigned to you?
 - Do you think you would have had trouble completing this type of problem? Why or why not?
 - Do you feel that you are a good writer?
 - What type of writing would you consider these problems to be, and is this type of writing useful to you as an engineering student?
 - Why do you think they might be helpful for students in statics?
 - Why might they not be helpful?

(Thank you. You are doing great.) Next, I want you to take a look at this problem. Read over the problem statement and the given figure, and give me your initial thoughts about them.

Next, go through and begin to solve the problem. You do not need to actually solve it, but at least set it up. As you work through it, say out loud any thoughts that pass through your mind, no matter how trivial. In essence, I want you to continuously let me know what is going on in your mind as you work through the problem.

(be sure to remind them to say what they are thinking if they are not doing so)

8. Follow-up questions:
 - Why did you...? (probe them about the decisions they made, especially if they were incorrect or seemed like guesses)
 - Is there a method or process that you are using to solve this problem?
 - To you, what is a free-body diagram?
 - What are reactions?
 - If moments calculated by inspection:
 - Why could you simply look at the figure and calculate the resulting moment at point A for each force?
 - How would this problem be different if the forces were not directed along the coordinate directions?
 - If moments calculated by cross product:
 - Why did you choose to use the cross product to find the moments at A?
 - Was it completely necessary in this case? In what case would it be?
 - Would you call this a difficult statics problem? Why or why not? How could it have been made easier? Harder?

Appendix C1. Researcher Background and Examination of Potential Biases

My desire to conduct research on statics education stems largely from my experiences as a student and educator. While in school as an undergraduate, I witnessed some friends and other peers leave their engineering major or delay graduation because of their difficulties and poor performance in statics. As a tutor for the course during my upperclassman years, I saw more closely some of the challenges that some students faced despite considerable effort and time spent studying for the course, and I desired a better understanding of how I could help them able to become more successful. Since coming to Virginia Tech for graduate school, I have had the fortune of serving both as a teaching assistant and instructor for the course. These experiences have provided me additional insight and motivation for continued exploration of the kinds of challenges facing students.