Full Paper

Introduction and Motivation

Writing is one method used to prompt students to reflect on their own thought processes. Eliciting students' explanations in the form of text, or writing, can provide lecturers with information about students' thinking (Self-citation). One purpose of assessment is for teachers to better understand students' thinking, through their conceptual frameworks, so that instruction and assessments can be designed accordingly (NRC, 2001). Developing assessments that challenge students to reflect on their own thinking and articulate their ideas leads to engaging students metacognitively, or on a deeper level of understanding (Smith & Tanner, 2010).

Often in engineering courses, students adopt algorithmic problem-solving approaches without demonstrating conceptual reasoning. Engineering programs tend to favour procedural knowledge over deep understanding, which has been shown to lead to problems in student retention (Danielak, Gupta, Elby, 2015), and does not promote the importance of conceptual understanding. Streveler et al. (2014) argue that low conceptual understanding of fundamental engineering concepts is due to misconceptions that limit or prevent conceptual change. One strand of research focused on changing aspects of students' incorrect conceptual understanding has investigated the role of explanations and language in forming and changing conceptual understanding (Sinatra & Pintrich 2003).

Students' deepened understanding, fostered through their engagement with writing, has the ability to enhance acquisition of important concepts in engineering when supported by focused teaching. The think-aloud method (van Someren, Barnard, &Sandberg, 1994), which can be modeling through writing, is a way for instructors to understand a student's thought processes. Teachers can then identify any incorrect assumptions or analogies the student exhibits 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. Writing may also be used to prompt students to reflect on their own thought processes when solving problems, prompting their own revision of incorrect and/or inconsistent knowledge. However the think-aloud method, or other interview-type methods, are time-consuming for teachers and require valuable resources to conduct and evaluate. Adding a written, or explanatory component to problems is one approach that can also elicit conceptual reasoning.

We present two different studies that propose writing, to elicit student reasoning, is a useful approach in teaching, learning and evaluating conceptual knowledge. The purpose of this paper was to identify and compare the affordances of using students' written explanations based on the type of given problem and written response. Two separate studies utilized the framework of writing to learn, to examine its impact on conceptual knowledge. Table 1 provides a summary of the research questions and general design in both studies.

Table 1. Individual Study Overview

Study	Research Question	General Design
1	In what ways do students utilize process problems that may work to develop conceptual knowledge, particularly through reflection?	Quasi-experimental study in which statics students were given required writing homework approximately once per week in an attempt to enhance conceptual knowledge development.

2	How do students respond when asked to write their reasoning, or explanations, of their answers to conceptually-based questions?	Case study that incorporated a component for students to provide written explanations to the Signals and Systems Concept Inventory questions, in an attempt to evaluate students' conceptual understanding.

The remainder of the paper is organized as follows: a literature review on knowledge development and evaluation in engineering, a summary of each study's methods and findings, an overarching discussion section for both studies. The paper concludes with final remarks, or takeaways, based on the incorporation of writing as it relates to conceptual understanding.

Literature Review

Conceptual and Procedural Knowledge Development

Theoretical arguments and empirical findings have been used to advance positions supporting a procedures-first or concepts-first approach to instruction in mathematics, for example. Rittle-Johnson et al. (2001) and Alibali (2001) propose the two types of knowledge to be 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. The case may exist where neither type is learned as well, making it more difficult to develop. In this study we are interested the ways in which conceptual knowledge can be developed through problems that are based on procedural knowledge.

While engineering can often favour procedural knowledge over deep understanding, procedures that lack connections with conceptual knowledge may deteriorate quickly and are not reconstructable. They may be only partially remembered and combined with other sub- procedures 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 (Hiebert & Lefevre, 1986). Thus, conceptual knowledge development is an essential component of learning in engineering, where procedures typically form a large portion of what is taught and assessed.

The development of conceptual knowledge in engineering can be particularly troublesome for students notwithstanding their ability to retain and follow 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 engineering subjects is not only a problem itself, but it may also give rise to problems involving deficiencies in procedural knowledge.

Evaluating Conceptual Understanding and Impacting Conceptual Change

Concept inventory tests have been developed to assess students' conceptual understanding in certain subject areas. Teachers typically use concept inventories to evaluate students' understanding of certain topics within a subject. The results, which provide information on students' understanding or lack of understanding, can be used to inform course material and the presentation of information on the relevant topics (Bailey, Johnson, Prather, Slater, 2009). However, concept inventories have limitations when they typically rely on True/ False or Multiple Choice Questions to identify misconceptions. Conventional concept inventories do not provide the capacity for lecturers to analyse students' reasoning, nor the opportunity to incorporate feedback to students on their misconceptions. A critical concern regarding conventional concept inventories is that an assessment of content knowledge is not the same as a measurement of conceptual understanding (Libarkin, 2008).

Another approach to evaluating conceptual understanding is through the analysis of written data. Constructed response measures allow students to describe their understanding through written explanations, and can be incorporated with the multiple-choice format. Automated evaluation methods of constructed response answers have been shown to validly detect understanding and are capable of accurately capturing students' scientific ideas as accurately as human-scored explanations (Beggrow et al., 2014). The process of analysing students' explanations can elucidate how students associate concepts, gain better insights into students' levels of understanding of these concepts, and subsequently reflect on their teaching key concepts and options to to improve and enhance their own practice.

Methods

Studies 1 and 2 were conducted separately. Both studies sought to examine the impact of incorporating writing on students' conceptual knowledge— either knowledge development or evaluation. Study 1 used "process problems" that required students to explain, using only words, the process that they used to solve a statics problem. Study 2 utilized the Signals and Systems Concept Inventory questions, and required students to provide a written explanation for their multiple-choice selection to each question. We categorized responses by the type of problem and student response explanations to evaluate the impact of writing on conceptual knowledge.

Study 1

Study 1 researchers conducted a quasi-experimental study in which statics students were given required writing homework roughly once per week in an attempt to enhance conceptual knowledge development. The "process problems" required students to describe their solution process for a particular homework problem using only words – no numbers, symbols, or figures could be used. The assignments were graded by teaching assistants using a rubric provided by the researchers and were returned to the students with feedback. The portion of the study described here comes from three implementations that took place over a period of three academic terms, two terms at a Large Mid-Atlantic Public (LMAP) institution in the United States and one term at a Small Mid-western Private (SPri) institution also in the United States. During the study, interviews were conducted with approximately 10 students per implementation; part of these interviews sought information related to how students interacted with the process problems during the semester.

Data Collection and Analysis

The data reported in this paper was obtained from semi-structured interviews conducted with a total of thirty-two students in the United States. Thirteen students were from a Spring 2011 (Pilot) implementation at the Large Mid-Atlantic Public (LMAP) institution, ten were from a Fall 2011 implementation at LMAP, and nine were from a Spring 2012 implementation at the Small Mid-western Private (SPri) institution. In Spring 2011, two sections participated as experimental sections while one section was used as a control (for the quantitative data collected but not discussed here). Enrollment for each course section at the SPri institution during the study was limited to 20 students. Two sections, both receiving the process problem intervention, participated.

In all cases, interviews were conducted near the end of each term for each implementation. The interviews were audio-recorded and later fully-transcribed. The analysis process began with an initial pass at coding for instances of demonstrated conceptual knowledge and/or procedural knowledge as a result of interacting with the process problems. Other passages that seemed particularly important or significant with respect to the study goals were also marked as consistent with an open-coding process (Seidman, 2006). After the initial coding pass was completed, each interview transcript was condensed into a passage summarizing the participant's 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.

Results

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. During analysis, these actions and explanations were grouped into four categories: self-explanation, checking understanding, organizing solution process, and generalizing solution process. There were also some students who reported going through little to no reflection.

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.

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 states: *"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?*"

3. Organising 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."*

4. Generalising 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."

Scott, a 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.

Interpretation and Conclusion

At the onset of this study, it was hypothesised 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. The results 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).

Study 2

The second study conducted at an Australian university utilized conceptually-based questions to evaluate students' understanding. Study 2 engaged students in writing brief explanations for their multiple-choice selections, necessitating them to reflect on their selections to each question through an explanation. To accomplish this, we incorporated a textual component to the multiple-choice questions, by augmenting a subset of 15 questions from the Signals and Systems Concept Inventory, SSCI, (Wage, et al., 2005), and later had students reflect on the process in an interview with the researchers.

Data Collection and Analysis

The data obtained for Study 2 was collected from the administration of the multiple-choice and text component of an online SSCI test to undergraduate electrical engineering students over two different semesters. This course had prerequisite courses that included material for analogue and digital signal processing.

The researchers conducted a semi-structured interview with a small group of students who took the concept inventory test after the first administration. Participant selection was limited to the students who volunteered. The interview was recorded and fully transcribed in order to perform a qualitative analysis of the student feedback regarding their experiences in which they explained their reasoning. The analysis process classified participant responses as they related to the process of writing and conceptual knowledge and/or procedural knowledge.

Results

Participants had different views on the usefulness of the writing component; some described providing their explanations to multiple-choice questions as useful in developing conceptual knowledge, while other participants reported that the writing component was useful in providing partial marks. During analysis, participants' responses were grouped into four categories: conceptual understanding within the university system, personal value of providing explanations, and generalizing solution process. There were also some participants who indicated no connection between providing written explanations and eliciting

1. Conceptual understanding fit within university system

Participants 7 and 4 reflection on explaining and thinking about their choice of the multiple- choice selection was how they related the outcomes of the writing process to their experiences with other university assessments. Participant 7 states, *"I think it comes down to how Uni is structured. When you're studying for an exam, you learn how to do the exam. You don't learn how to do the course content. That's probably what it comes down to… saying, I've seen this before, but I don't know the reasoning behind it. I just know how to answer it."* This type of reflection on how their prior experiences in the university system favoured procedural knowledge allowed them to acknowledge the differences in procedural actions, more so than knowledge, and conceptual knowledge. Participant 4: confirmed by saying, *"Or remember how to do rather than remember how to actually… rather than knowing. "*

2. Personal value of providing explanations

Students' reflection on the strength of their own conceptual understanding, elicited by providing written explanations, helped some students to evaluate how well they know a given concept. Participant 5 stated, *"I found it quite nice to be able to try and explain what you know.* Participant 3 "*the fact that you're prompted to actually come up with wording for… why are you thinking this way… that was good enough for me... because that made me think… this is what I know, this is what… can't explain yourself."*

3. Future use and importance of conceptual understanding

Participant 3 also recognised the role of conceptual understanding in future scenarios, such as its value in real world contexts. They stated, *"if you're the only engineer in that kind of environment, you may not be able to ask… someone else technically questions, but at the very least… the process of going through something and being able to figure out what you do and do not know, means that, worst case scenario, you don't kill someone."*

4. No connection to conceptual knowledge

The feedback from Participants 1 and 2 were instances where the underlying conceptual knowledge, which was intended to be elicited by the conceptually-based questions, was not evident from how students' reflected on providing an explanation. Participant 1, said "*I don't know how to explain, 'cause some of them are just calculations. And I guessed some of the answers."* Participant 2 simply states *"The test is easy, but I really don't know how to explain it*." These types of responses indicated that certain students took a procedurally based approach to answering the questions, that are not intended to require much calculation.

Interpretation and Conclusion, Study 2

The results from participating students' reflections on the writing process showed that some students recognised the use –and importance-- of conceptual understanding, and others had difficulties explaining underlying concepts beyond a procedural framework. The researchers of this study acknowledge the limitation, that asking students to provide written explanations to elicit reflective and more conceptual understanding does not directly account for some students' inability to express their understanding through writing. Future work in this area can incorporate training for students on the process of reflecting and writing to elicit their own conceptual understanding.

Final Remarks

While the setting for the two studies was in engineering, developing students' capabilities for reflection, independent learning, and metacognition are fundamental graduate attributes applicable to all disciplines. Educators who require students to reflect on their thinking through textual explanations can promote the revision of incorrect and/or inconsistent knowledge, leading to improved conceptual knowledge development. Assignments or activities that include more incidental writing will engage students in more freethinking and reflection (Essig et al., 2014; Hawkins, Coney, & Bystrom, 1996), and can lead to a richer understanding of technical concepts. Regardless of the type of problem, or questions, we recommend providing students with feedback on their thought processes that they can use to formatively evaluate their own understanding.

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