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Motivating and Building Engineering Majors Conceptual Knowledge in Chemistry

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Introduction

To improve engagement and learning in introductory foundational STEM courses, many research-based institutions have invested in teaching faculty members who have subject matter expertise, a deep understanding of effective pedagogy and experience and/or interest in adopting evidence-based teaching practices. With support from the National Science Foundation, Stevens Institute of Technology began working with cohorts of teaching faculty who teach the core Science, Math and Engineering courses taken by 85% of first year students. Faculty worked together for three years to change their instructional practices with the goal to increase the use of active learning and facilitate development of deep and transferable learning [1]. The General Chemistry curriculum at Stevens Institute of Technology, as part of this NSF Foundations project, was redesigned to facilitate student engagement, motivation and interaction with the content using a number of different strategies including peer to peer instruction, active learning and online resources and weekly quizzes to facilitate self-assessment and reflection.

In this paper, we describe initial efforts to incorporate one type of metacognitive strategy (i.e. prompt students to think about and reflect on their learning and understanding of the content taught each week) in the General Chemistry course. Key questions of interest include: What is the nature of student responses (conceptual or procedural)? Do responses vary by course week and/or gender? What is the relationship between student response (conceptual or procedural) and their performance on the exam?

Research has demonstrated that active and collaborative instruction coupled with various means to encourage student engagement lead to better student learning outcomes irrespective of major or academic discipline [2], [3]. Further, prompting students to reflect on what they do or do not understand is a key strategy for improved student learning [3], [4], [5]. In courses, these reflection practices known more formally as metacognitive strategies can be integrated into quizzes, homework assignments, and exam preparation so that it becomes a second nature method of practice [4]. The ultimate goal is for students to take action on an on-going basis to address topics they don't understand either by reviewing the topics and/or asking the instructor or others for clarification to facilitate the development of deep and transferable knowledge.

Background.

Metacognition can be defined as the purposeful thinking about one's own thinking [6], [7]. Specific strategies to promote metacognition in the classroom, including pre assessments, identifying the "muddiest point" for a lecture or series of lectures, reflective journals, one minute papers, and exam "wrappers" (surveys given to students after the exam prompting them to reflect on their exam preparation), have been implemented in multiple foundational courses including Biology, Chemistry and Psychology [2], [4], [8], [9]. The one minute paper, muddiest point and exam wrapper are commonly used in General Chemistry classes in large part because they are relatively quick and easy methods and provide information to both the instructor (to improve teaching) and the students (to improve learning) [2], [8], [9], [10]. For the “Minute Paper” the instructor takes a few minutes at the end of class for students to answer two questions, generally what they learned and what question(s) remains unanswered. After reviewing student comments, the instructor can address the most common comments in the next class as well as quickly assess a student's learning and understanding [8]. Eliciting information from students on the topic that is most confusing, or the “muddiest point”, has been applied for years in many different classrooms including General Chemistry [8], [9], [10]. For example, King [10] used clicker questions in a large enrollment General Chemistry course to have students anonymously identify the “muddiest point” from a selection of topics. This method allowed for rapid detection of the topic areas students were struggling with and the instructor could then address these issues during class. It was found that students identified more calculation/procedural topics as the “muddiest point” even though 75% of the topics to choose from were conceptual in nature [10]. Casselman and Atwood [11] embedded metacognitive training into an online homework system with weekly quizzes and practice tests for a first semester General Chemistry course. Students were asked to initially predict their performance on the assessments and then afterwards received detailed feedback on the accuracy of their prediction and their performance [11]. The students then specified the Chemistry topics they would focus on and created a study plan to do so. Casselman and Atwood [11] noted a slight increase in performance (about 4% higher on summative assessment exams and the ACS final) for those students who received this “metacognitive training” when compared to the control group [11]. Cook et al. [12] presented a seminar on metacognitive learning strategies after exam 1 to General Chemistry students and found performance improved on subsequent exams.

Approach

To facilitate increased student engagement and interaction with the content, the General Chemistry I and II curriculum was redesigned beginning Fall 2017. Large lectures and recitation were replaced with sections of approximately 55 to 60 students each meeting three times per week with increased opportunities for active learning both inside and outside the classroom, including peer interaction, group problem solving, and self-assessment and reflection. General Chemistry II, the focus of this study, covers the following topics: Kinetics, Solutions, Equilibrium, Acid-Base Equilibrium, Buffers, Titrations, Thermodynamics (i.e. Entropy, Gibbs Free Energy, Electrochemistry, Nuclear Chemistry, Transition Metals).

Strategies for self-assessment and reflection were embedded in weekly quizzes delivered via the course’s learning management system. These quizzes consist of a series of multiple-choice conceptual and calculation-based questions. The students have three-and one-half days to complete the quiz and two attempts are granted so, if they choose, they can retake the quiz after additional study and review. To encourage students to reflect on what they learned over the week and what they still need to focus on, students are asked to answer two questions, labeled as a weekly report: "What did I learn this past week [from list of chapters covered that week]?" and "What remains unclear to me and that I need to review further [from a list of chapters covered that week]?" The questions, asked at the end of each quiz attempt, serve to prompt students to reflect on what they have learned and how well they understand the topics covered during the past week. During this preliminary study, a master's level course assistant, read all reflections and provided summaries of the topic areas with which the students were struggling. With this information, some in-class questions and group worksheet problems were designed to address these problematic areas.

In this paper, we focus on student responses to Question 2: "What remains unclear to me and that I need to review further [from list of chapters covered]? We examined materials from weeks 1, 2, and 3 which preceded the first in-class exam administered in a common exam period. The exam consisted of 22 multiple choice questions and four constructed response items. For this analysis, we examine performance on the multiple-choice items only.

Sample. This analysis focuses on 120 first year students; all but five were Engineering majors. The students (N=75 males and N=45 females) were enrolled in one of two regular sections or the Scholars section of General Chemistry II in Spring 2020. The Scholars section (honors) consisted of students who either opted for the Scholars section based on their A performance in General Chemistry I or their inclusion in the University's Pinnacle Scholars program. The two faculty who taught these three sections were part of the NSF Foundations Project, involved in the course redesign and have taught this course for many years at Stevens Institute of Technology.

Coding. Responses were read and categorized into eight categories (All Clear, Conceptual, Both, Generic, Non-specific, No response, Other, and Procedural). See Table 1 below. All responses to Q2 were coded independently by two project staff. Codes were compared and discrepancies resolved. The Inter-Rater Agreement between the coders was 88% overall.

Table 1. Codes and Examples of Responses.

Codes	Definition	Example Responses--Q2 What remains unclear to me and that I need to review further for the exam?
AC	All Clear (no problems)	There's not much that is bothering.
B	Both concepts and procedures	I need to further review the integrated rate law and graphing of the different rate orders.
C	Concepts	What remains unclear to me is how or why the vant' hoff factor varies theoretically vs experimentally.
G	General or Generic: Not specific concept or procedure	So far nothing seems unclear to me however I definitely need to memorize the formulas and calculations since there is a huge amount present in this week's chapter.
NR	No Response	
NS	Non-Specific: Response could refer to concepts or procedures; which aspect of a topic is troubling not specified..	Enthalpy of solutions still remains unclear to me.
O	Other: Generally off topic.	I am not confused about anything currently. (For question 10, I got 0.02 but that's not an answer choice).
P	Procedures & Calculations	The only thing that I need to review further is the equation that we use to calculate what the order of the reaction is when given the concentrations and rate values.

Results and Discussion

Student responses were coded for weeks 1, 2, and 3. 85% of students provided thoughtful reflections each week; 10% no response; 5% generic or nonspecific responses. See Table 2.

Nature of student responses. Table 2 shows percentage of responses by category and week. Except for week 1, higher percentages of students indicated concern over their understanding of procedures than understanding of concepts. On average, across all weeks, 41% had concerns about procedures/calculations and 28% had concerns about concepts.

Table 2. Percentage of Responses by Category and Week.

Response Type	Week 1	Week 2	Week 3	Overall Weeks 1-3
All Clear (AC)	12	3	10	8
Both (B)	3	7	3	4
Conceptual (C)	38	25	22	28
General or Generic (G)	3	3	3	3
No Response (NR)	8	8	14	10
Non-Specific (NS)	3	6	5	4
Other (O)	0	1	0	0
Procedural/Calculation (P)	33	48	43	41
Total (%)	100	100	100	100

Example of student responses (Week 1). In week 1, the topic area is Kinetics and in particular reaction rates and rate laws. Conceptual response examples included: i) "I need to further review all of the orders and correlating charts, formulas, and units." ii) "I need to review further the integrated rate law for each order." Procedural response examples included: i) "I still need to review how to find k." ii) "I think I can focus more on the calculations that sometimes arise with reading experimental data to determine rate law." In class, the Monday following the quiz, one conceptual and one procedural question on integrated rate laws was reviewed at the beginning of class. The conceptual question focused on interpreting data via a graph. The procedural question focused on calculating rate given other data.

Example of student responses (Week 2). In week 2, the topic area is Kinetics and in particular reaction mechanisms, and the effect of temperature on rate, the energy barrier, the Arrhenius equation and use of catalysts to speed up a reaction. Conceptual response examples included: i) "I am still working to better understand temperature in kinetics and activation energy." ii) "I need to review how the catalyst affects the rate of the reaction since it was less done." Procedural Response examples include: i) "Something that I need to further review is how to determine the rate law by using the slowest reaction step." ii) "A few things that still remain unclear to me are finding activation energy using the Arrhenius Equation for some of the problems where it is unclear what values to plug in but I am practicing all the different possible problems." iii) "One thing that is still unclear to me that I have to review a little more is finding the rate law for a reaction with a fast first step." In class, following the quiz, one conceptual and one procedural question on reaction mechanisms and the Arrhenius equation was reviewed at the beginning of class. The conceptual question focused on determining what happened to the activation energy when temperature changed. The procedural questions focused on determining the rate law for a reaction, given data for a reaction with a fast first step; and finding activation energy using the Arrhenius equation.

Example of student responses (Week 3). In week 3, the topic area was solutions and in particular solution concentrations, solubility and colligative properties including vapor pressure, osmotic pressure and freezing and boiling point depression. Conceptual responses included: i) "I still need to work on understanding colligative properties and what exactly osmotic pressure is. I do not understand the concept of osmotic pressure however, I am able to perform calculations for it." ii) "I am still unsure about the van't Hoff factor and when it must be applied." Procedural responses included: i) "What remains unclear to me that I need to review further for the exam is boiling-point elevation and freezing-point depression." ii) "I need to review vapor and osmotic pressure." iii) "Some things that are still unclear to me are the steps into determining the freezing and boiling point of an element/mixture." In class, following the quiz, how to calculate the colligative properties was reviewed by looking at specific problems for vapor pressure, osmotic pressure and freezing and boiling point depression. Also, the van't Hoff factor was reviewed.

Despite variation in student reflections of what material they were unclear about in the previous week and what they needed to review further, student performance overall was high on the exam administered in week 4, for this set of students. Figure 1 shows the total percent correct on each question in exam 1 coded by conceptual (C), procedural/calculations (P). and both (B).

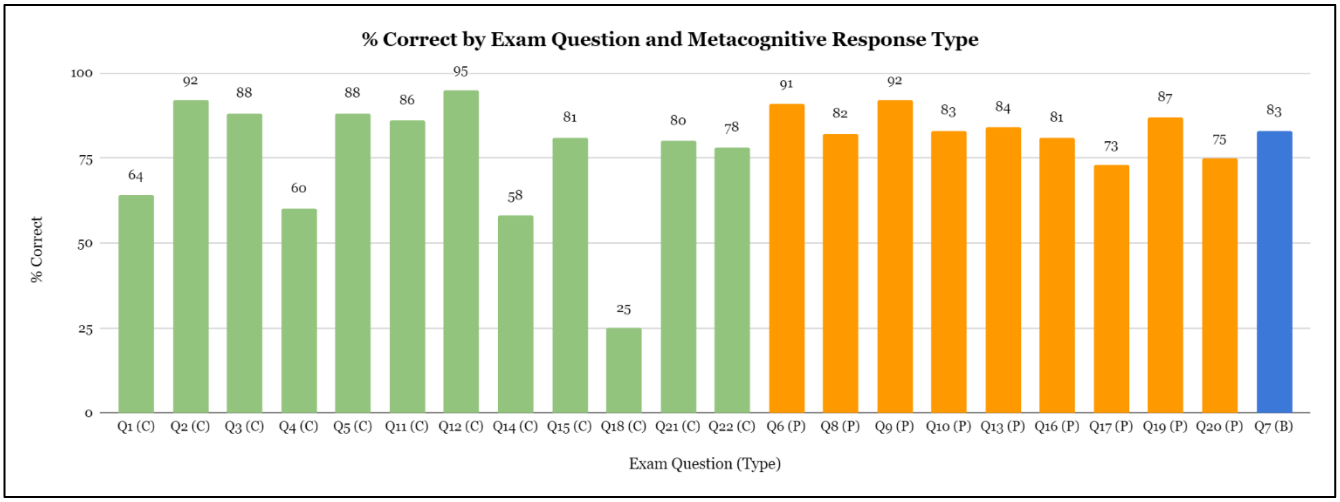

Figure 1. Percent correct for exam 1 items corresponding to exam 1 material.
***C indicates Conceptual, P indicated Procedural and B indicates Both.**

Gender comparisons. Percentage of students answering each question correctly by type of question (conceptual or procedural) and gender is provided in the next three figures (2–4), corresponding to topics covered in weeks 1, 2, and 3.

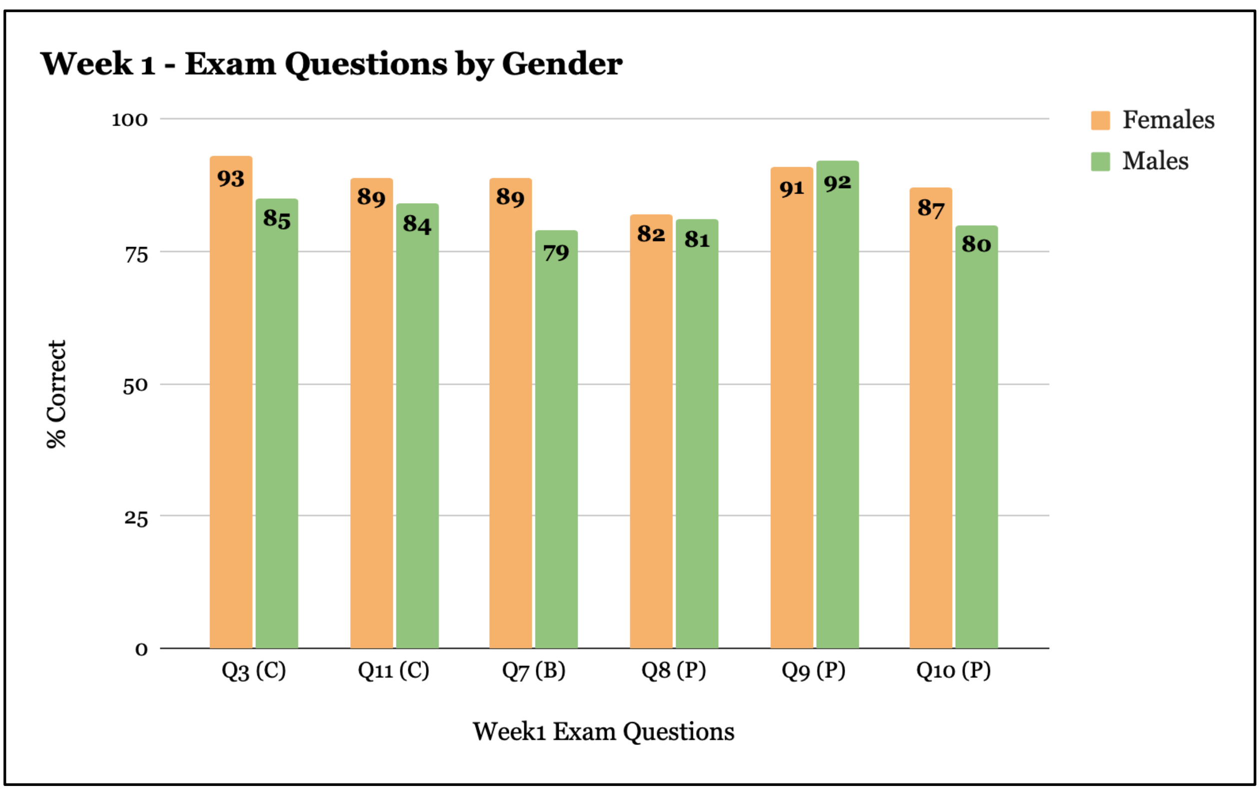

Figure 2. Percent correct by gender on exam 1 for items corresponding to week 1 material.

For exam questions corresponding to material covered in week 1, performance was high with 79% or more of students answering each question correctly (see Figure 2). Females tended to outperform males on the conceptual questions (Q3 and Q11), one procedural question (Q10), and Q7 that was both conceptual and procedural.

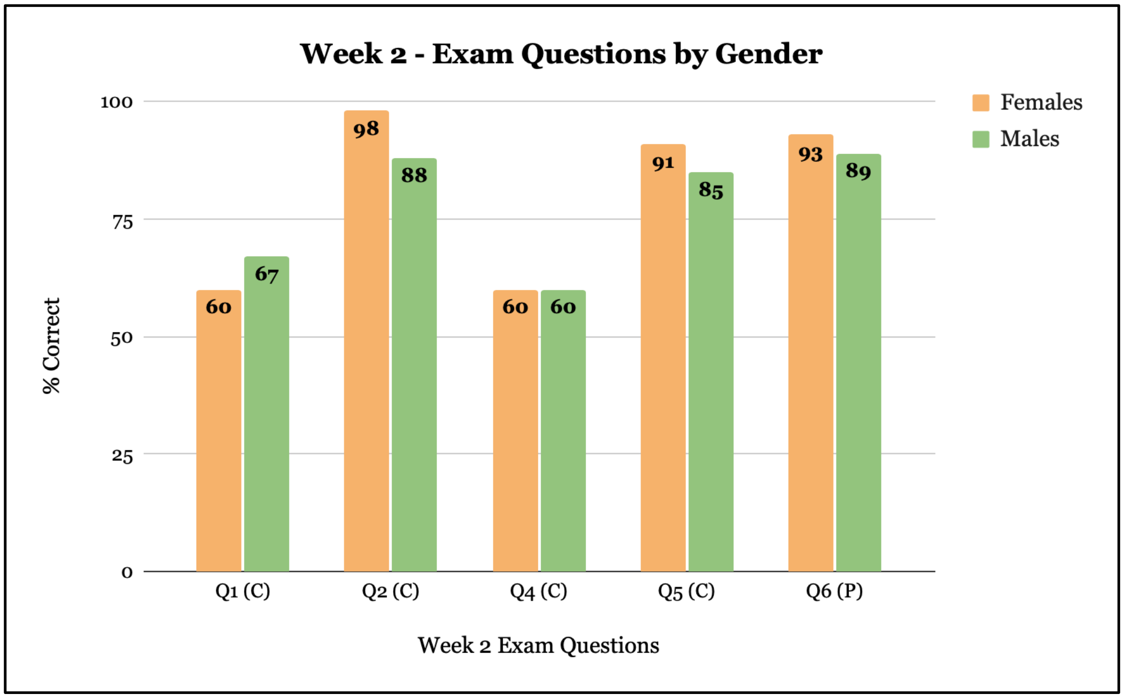

Figure 3. Percent correct by gender on exam 1 for items corresponding to week 2 material.

Overall, females performed better than males on 3 of 5 items on exam 1 that related to material covered in week 2 (see Figure 3). These conceptual and procedural items (Q2, Q5 and Q6) can be interpreted as easier than the conceptual questions (Q1 and Q4) based on exam performance.

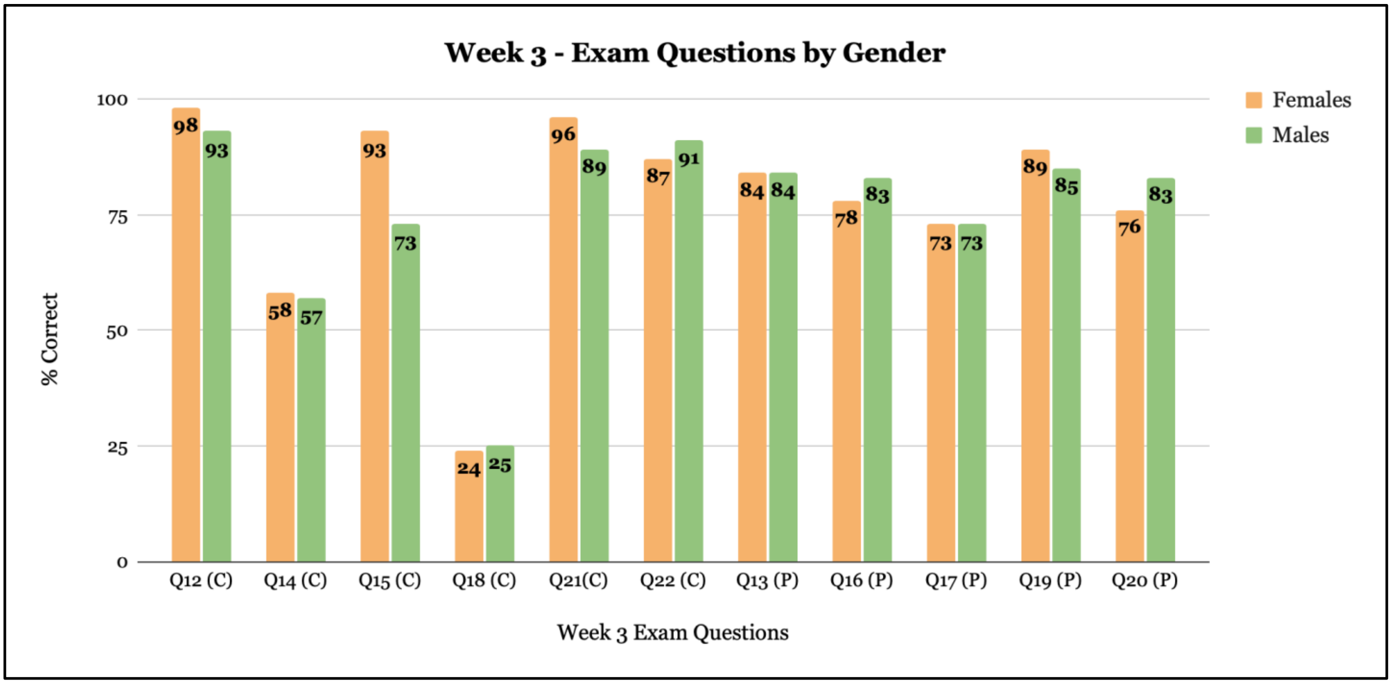

Figure 4. Percent correct by gender on exam 1 for items corresponding to week 3 material.

For week 3, there were fewer differences in performance by gender than was seen in weeks 2 and 3 and there was a much wider range of item difficulty (see Figure 4).

Correspondence between reflection and performance. Table 3 provides several examples of the correspondence between what students indicated "remains unclear to me and that I need to review further" and their performance on items that were consistent with their reflections. For example, Student A indicated they needed to review further concepts. She performed well on conceptual questions (100% correct) but poorly on procedural questions (0% incorrect). Student F indicated that "*So far, nothing seems unclear*." This student did well on conceptual questions (100% correct) but did not do well on the procedural question (33% correct). The students shown in Table 3 were purposely chosen to showcase the trends between their self-reflection on topics while learning the material and their subsequent exam performance on conceptual and procedural questions.

Table 3. Examples of correspondence between metacognitive response and performance on exam 1 by item type.

Student	Gender	Student's Metacognitive Response (Week 1)	Performance - Conceptual Questions (Exam 1 Week 1)	Performance - Procedural Questions (Exam 1 Week 1)
A	Female	Conceptual (C)	100%	0%
B	Female	Procedural/ Calculation (P)	50%	100%
C	Female	All Clear (AC)	100%	100%
D	Male	Conceptual (C)	100%	33%
E	Male	Procedural/ Calculation (P)	50%	100%
F	Male	All Clear (AC)	100%	33%

Summary and Conclusions

In this study, students were prompted to reflect on their understanding of course material on a weekly basis. On average, approximately 85% of students provided thoughtful reflections each week; 10% no response; 5% generic or nonspecific. The majority of student responses specified particular concepts (e.g., "*Im [sic]currently most confused about how the natural logs are represented. I understand that they are significant in first order equations but i don't get the real world causes.")* or procedures (e.g., "*Utilizing graphs to determine reaction rate values and reaction orders still remains kind of unclear to me."*). Generally, females did better on the conceptual exam questions than males, especially for material covered week 1. The more difficult exam items showed less variation between males and females across weeks. Preliminary findings suggest variation in correspondence between student reflection and exam performance. For some students, if they said they were unclear about concepts, their performance on the exam was high for conceptual items. For others, their performance was poor on item types corresponding to concepts or procedures for which they expressed no concern; presumably, they thought they understood the material, but their performance indicated otherwise. The strength of the correspondence between student reflection and exam performance is constrained by relatively easy exam items, for this first exam, and lack of information on the extent to which students followed through with their plans to review material that they were unclear about. Further, the preliminary analysis suggests that students may not be accurate in their perceptions of how well they understand the material covered each week.

Moving forward, we recommend that all faculty examine student reflections on a weekly basis with special attention to (1) those who are struggling with everything (code non-specific); and (2) common areas of concern which could benefit from further review/attention. With this important knowledge, faculty could routinely make sure to address issues in the first five minutes of class. Also, faculty could test student's expressed areas of difficulty by asking in-class questions (i.e. polling) with subsequent student discussion. Drawing attention to student reflections, allows students to observe that assignments have meaning (beyond a grade) and that a faculty is committed to improved learning for all students. These strategies and self-observations may motivate students to routinely reflect and become more self-directed learners.

Future Work

Future work includes completing analysis of the reflections from all weeks of the semester (weeks 4 to week 14) and comparing them to the corresponding exams as well as the final American Chemical Society conceptual exam. Differences in student responses across sections will be examined which may signal differential emphasis on key topics by the six instructors. Work will be done to quantify the correspondence between students' reflections and their performance on the subsequent exam. The overall goal will be to develop an effective method to encourage students to monitor their learning and level of understanding on an on-going basis.

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