Experiences with Formative Assessment in Engineering Classrooms

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ABSTRACT

Assessment in many engineering courses is mostly summative in nature. We have introduced an electronic Classroom Communication System (CCS) into undergraduate engineering courses to provide students with formative assessment on a regular basis. Experiences with the system are presented, including both student and instructor evaluations. Students like it because it is anonymous and lets them know in a timely manner when they have difficulty understanding new concepts. The system also helps inform the instructor about student comprehension of various concepts, well in advance of an examination, resulting in better retention of fundamental concepts. The system can help an instructor adjust the pace of the course to match the aptitude of the students. Therefore, instructors might reduce the variance in students' conceptual understanding of fundamental concepts early in the course, allowing for more uniform coverage of advanced topics later in the course.

Keywords: active learning, formative assessment, personal response system

I. INTRODUCTION

Traditional engineering instruction provides a learning environment that centers largely on transmitting domain knowledge from the professor to the students in a classroom setting. Typically students apply these concepts by completing homework assignments that are often evaluated at a rudimentary level and returned to students in a less than timely fashion. Misconceptions and misunderstandings can linger in such an environment and may not be discovered until the student is examined at the end of a unit. Summative assessments provide information about students' understanding of domain knowledge, but are usually not systematically used as a learning opportunity for students.

A key finding from recent research in learning sciences is that effective learning environments are those that center on the learners' conceptions, abilities and needs, assessment items and methods, and issues of community in addition to centering on the domain knowledge to be learned. The interaction of these four major dimensions form the How People Learn (HPL) framework described in a National Academy of Science (NAS) Report, entitled *How People Learn: Mind, Brain, Experiences and School* [1]. The committee observed that the designers of effective learning environments blend together various learning activities that consider these four dimensions. The rationale for including these dimensions is grounded in research on human learning for a range of learners and in a range of learning settings. The NAS report synthesizes research findings of effective learning environments and human learning determined by the fields of cognitive sciences, psychology, and education. Therefore, our assumption is that these same dimensions are relevant to second and third year college students, building on their physics, chemistry, and mathematical knowledge to solve problems in biomechanics and biotransport.

Our overall objective was to improve instruction by designing an active learning environment that was more informed by the HPL framework. The design consisted of in-class and out-of-class activities. We used the VaNTH Courseware Authoring and Packaging Environment (CAPE) [2] and experimental Learning Management System (eLMS) [3] to develop tools that provide students with formative feedback while they attempt to solve engineering problems outside of the classroom [4, 5]. For example, an online Free Body Diagram Assistant [6, 7] provides students with formative feedback as they construct free body diagrams and can be used to systematically introduce them to all of the important supports and constraints encountered in basic mechanics

Our approach within the classroom environment was to present new concepts to students through a series of challenge-based modules [8, 9]. We chose this approach because it was a natural setting for introducing student-centered, community-centered, and assessment-centered activities into a knowledge-centered environment. We have previously described the design and effectiveness of challenge-based instruction [8–10]. The focus of the current manuscript is on the use of formative assessment in the classroom. Research indicates that formative assessment is one of the most effective instructional methods for supporting student learning [11]. Brosvic et al. [12] examined the effect of immediate feedback, delayed feedback, and no feedback on student performance when confronted with previously encountered questions on the final examination. They found a significant improvement in retention when students were initially provided with immediate feedback rather than delayed feedback or no feedback, and even greater retention when provided with multiple attempts on the initial encounter. Dufresne and Gerace [13] state: "Classroom assessment entails a shift in the classroom culture away from a teacher-centered, answer-dominated focus to a focus on students' mental processes as they are manifest in analysis and reasoning activities." VanLehn et al. [14] showed that learning was often enhanced once a student reached an impasse. Formative assessment can help bring students to that realization and provide both students and instructors with immediate feedback as they progress toward the learning goals. This can be accomplished by using class time to periodically ask carefully crafted questions that assess students' current conceptions of domain knowledge. These questions can expose students' preconceptions before a lesson, or review ideas recently taught in the course. In both cases, the questions help students identify an impasse in their understanding which can motivate them to engage in the instruction. Therefore, formative feedback primes students to learn.

Formative assessment based on a show of hands is often ineffective because student responses are not anonymous. Many students wait until other students raise their hand before responding, and many do not participate at all. Timely feedback in the classroom requires a method that provides nearly instantaneous and simultaneous responses from all students [15]. Although this can be successfully achieved without the use of technology, such as the use of flash cards [14], we use an electronic classroom communication system (CCS) to provide formative assessment to students during class. These systems have been used in a number of learning environments, including physics [13, 15–19], physiology [20, 21], philosophy [22], and public opinion [23].

Although we integrate CCS questions into our challenge-based modules, the technique can also be used effectively in traditional lecture-based courses. Our initial experience with a classroom communication system (CCS) showed this to be an effective method for providing formative assessment to students in engineering classes [24]. Students and instructors both agreed that a CCS made good use of class time. In addition, periodic use of a CCS uncovered concepts that students found particularly difficult. Our preliminary studies found a direct correlation between student performance and student participation via a CCS.

II. Methods: Formative Assessment in the Classroom

In this study we expanded the use of the CCS system to assess students' retention of fundamental concepts and the benefits of extended use of the system across the semester. We anticipate that the rapid feedback on conceptual understanding followed by in-class instructional activities, like peer and class discussions, will increase learners' retention of fundamental concepts.

We use a wireless (infrared) classroom communications system, the InterWrite Personal Response System (PRS) distributed by GTO CalComp, Inc. to assess students' current understanding of concepts (Figure 1). Students are assigned a unique transmitter unit at the beginning of the semester. They pick up their transmitter as they enter the classroom and return the unit at the end of class. During class the instructor poses multiple choice questions targeting key concepts for the class session. Students respond to the question by pressing a button on the transmitter unit. The signals from the units are collected by an infrared receiver at the front of the room connected to the instructor's computer. The system software quickly sorts the students' responses and displays the frequency of responses as a bar chart. This chart is projected after each question to provide the students and instructor with feedback on student's performance. The overall class performance on these questions dictates whether the class moves on to the next topic or goes back and reviews the current topic. In all cases, ample time is allowed for discussion of the results. If the class responds with an even distribution across items, the instructor would want to review the material to reduce this variance. If the question is more factual than conceptual, the instructor may choose to simply tell the students the correct answer and move on. In some cases students are not given the correct answer after the poll results are displayed, but instead are asked to

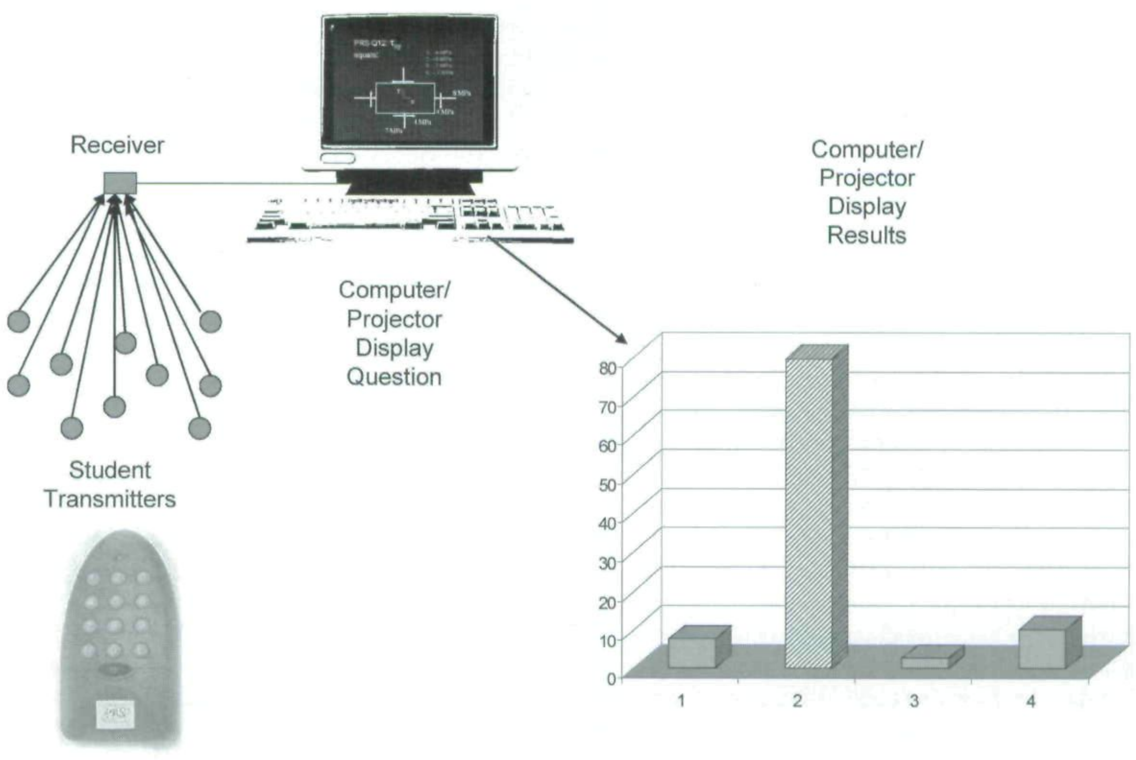

Figure 1. Personal Response System (PRS).

convince their neighbor that their answer is correct. The class is then polled on the same question. This gives students an opportunity to think about the options and revise their original response, rather than simply listening to the professor's explanation.

Simple formative assessment methods like the PRS require little effort to implement, but can have a large potential for keeping students engaged with classroom activities. Approximately 90–100 questions are asked over the course of the semester, with an average of about four questions per 75 minute class period, usually following the introduction of new or difficult concepts. Typically, every question results in a 100 percent response rate from the students, and students are often asked to talk with each other to reflect on the answers. Therefore, the flow of the class helps students to focus on key concepts. This active participation is a critical component in their learning. All questions are multiple-choice, with each incorrect answer traceable to a common misunderstanding. Polling takes no more than 30 seconds of class time per question, even with a large class of over 50 students. System set-up and break-down each takes about 5 minutes, not long enough to interfere with other classes that use the same classroom.

Although a CCS enhances the overall learning experience for the class as a whole, it does take some class time, particularly on the more difficult concepts, and may not be beneficial to the brightest students, who may be forced to sit through several iterations of unneeded remediation. To remedy this potential defect, we have made note of those situations where the CCS has identified particularly difficult concepts. We then built modules with CAPE that could provide individualized, formative feedback outside the classroom in subsequent years [4, 5]. We still ask the question in class so the students become aware of their misconceptions, and then assign the CAPE module for homework. Good students need little or no remediation, and the module might even provide them with more challenging problems. Intermediate students should be able to finish the problem within one or two iterations with the help of the formative feedback provided by the module. Students who are unable to work the problem with the aid of the module are asked to see the instructor or teaching assistant for help. Therefore, students who need help now gain extended practice on some of the more difficult concepts originally identified in class using the CCS.

We used the VaNTH Observational System (VOS) [25] to document the degree of formative assessment present in traditional and HPL-inspired biomechanics courses taught over a five consecutive semesters. This observational system is administered by a trained observer who codes the interactions between the instructors and the students using an instrument designed to capture HPL events in the classroom.

A student survey was used to capture students' reactions to the various instructional methods used in the classroom, including the CCS.

III. Results

More than 8,000 observations were recorded in traditional and HPL-influenced biomechanics classrooms over a total span of 2,000 minutes with the VOS. The incidence of formative assessment was found to be higher (30 percent) in the HPL classes than in the traditional sections of the same course (20 percent). The difference was significant (effect size = 0.95), and we believe this is primarily due to the use of a CCS.

PRS Q3:

A bone is composed of two segments of equal length. The density of the top segment is twice that of the bottom segment.

The center of gravity is:

1) Above the center of volume.

2) At the center of volume.

3) Below the center of volume.

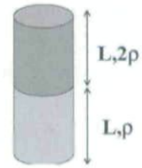

Figure 2a. Example of a typical personal response system (PRS) question asked in class.

We provide two examples of how the PRS system was used to provide formative feedback in an introductory biomechanics class. The first question (Figure 2a) was asked immediately after a short lecture that introduced the mathematical definitions of center of gravity, center of mass, center of volume, and centroid. Since only half the class got the correct answer (Figure 2b, solid bars), the instructor did not immediately provide the correct answer, but instead asked the students to discuss their answer with nearby students and explain why they thought it was correct. After a couple of minutes the students were asked the same question and the result is shown as the striped bars in Figure 2b. Half of the students whose initial response was incorrect were convinced by their peers to select the correct response. A short discussion followed for the benefit of those who still did not understand the difference between center of gravity and center of volume.

The second example illustrating the use of the PRS system follows an explanation of the sign convention and subscript convention used for shear stress (Figure 3a). Only about 30 percent of the class understood both conventions (Figure 3b). Without the PRS system an instructor might assume that the class understood these conventions, thus losing 70 percent of the class when presenting subsequent material. PRS results like this tend to jolt both the professor and the students. The professor begins to question the way the material was presented, while the students suddenly decide they should pay closer attention to the instructor. Although there is probably some benefit to both interpretations, the truth is that this is a difficult concept. In fact, even after the conventions were reviewed a second time, students still had difficulty when asked a similar PRS question (Figure 3c). Only after the conventions were reviewed yet a third time was the variance sufficiently reduced so the class was ready to move on to the next topic. Thus, the PRS system can provide valuable information to the instructor as well as formative feedback to the students. In addition, it tends to help set the right pace for the class and keeps it focused on the learning rather than on an instructor-driven goal of completing a prescriptive list of taxonomic topics.

To examine retention of key concepts in the course, twenty of the ninety PRS questions asked over the course of the semester were revisited on the final examination. Figure 4 shows that retention on the final exam, relative to initial in-class CCS performance, was significantly better on 12 of the 20 questions and significantly worse on only two of the questions ($p < 0.05$, paired t-test). Both of the latter questions dealt with memorization of factual information, rather than concepts. Question 2 probed their knowledge of the principal planes and question 14 required them to identify lever

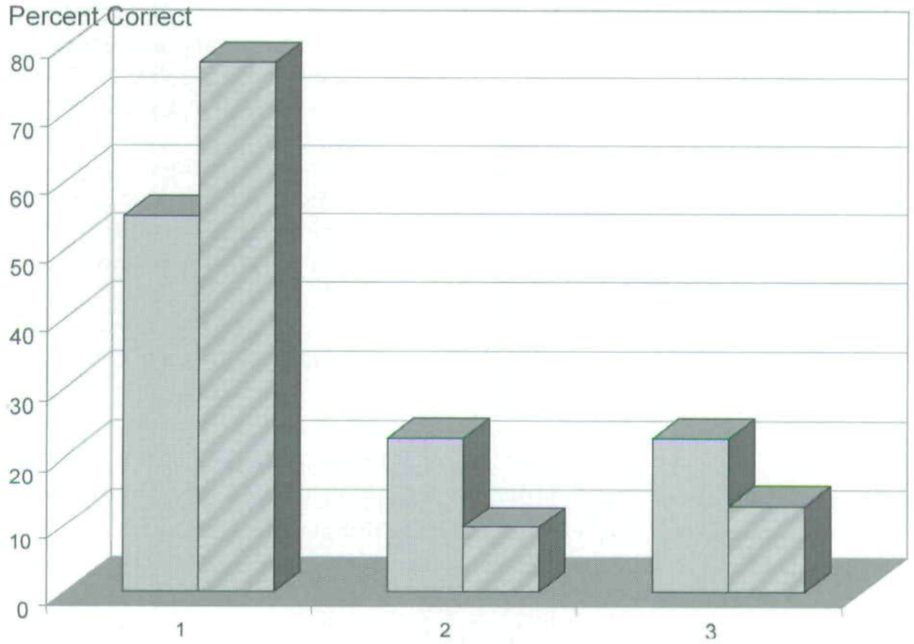

Figure 2b. Original student response to the PRS question in Fig 2a (first bar) and response after students discussed their answers with another student (second bar). The percentage of students selecting the correct response (first answer) increased from 52 percent to 76 percent.

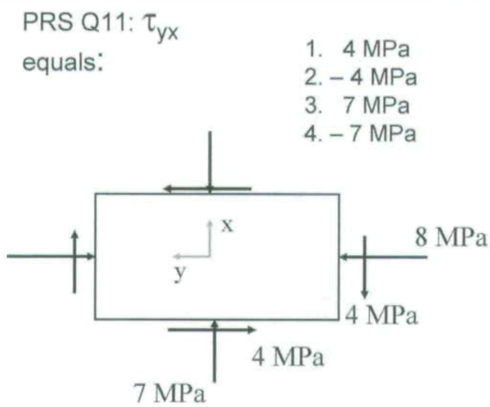

Figure 3a. PRS question used to gauge student understanding of the shear stress sign and subscript conventions. This was asked immediately after the conventions were explained in class.

classifications. Final exam performance was not significantly different from classroom performance on the other six questions. On four of these questions (q4, q10, q11, q18), 70 percent of the students answered correctly on their first attempt in the CCS session, so many students were either familiar with those concepts or they were relatively easy to comprehend using standard lecture methods. Keep in mind that the initial PRS questions were asked shortly after the material was presented in class, when the material was still fresh on students' minds. Some were discussed in depth and revisited multiple times using the CCS.

In an earlier study we found a strong correlation between student participation, as judged by the number of PRS responses in a semester, and student performance [24]. Because of the anonymous nature of the system, students present in class generally take the time to respond to PRS questions. Thus, the number of questions answered is primarily a reflection of class attendance. Student survey results also indicated that attending class was an important factor in doing well in an HPL class. This information was shared with students in later years on the first day of class and a participation grade was implemented. This was based primarily on PRS participation and accounted for 10 percent of the final grade. This grade reflected their participation only, and not the correctness of their response. Therefore, students were encouraged to participate, even if they were unable to answer a question correctly. Since all lecture material is available on the class Web site, some students chose to ignore the advice provided on the first day of class. The influence of class participation on student performance in the second year, following implementation of the class participation grade, is shown in Figure 5 for homework, exams, final exam and total points in the course. Clearly, student performance is still strongly associated with class participation. This indicates that students who participate in the learning activities have a stronger probability of being successful in the course.

A student exit survey was used to capture students' reactions to various methods used in the course. In particular, we asked students to rate several statements concerning the PRS system using a 5 point scale (1 = strongly disagree to 5 = strongly agree). Results are shown in Figure 6. Students liked the anonymity of the system, felt it was a valuable use of class time, stimulated them to ask questions and helped them pay closer attention in class. These are all critical components for creating an active learning environment that engages learners in activities that lead to increased retention of the domain knowledge.

IV. Discussion

Formative assessment is a key factor that contributes to the effectiveness of HPL informed instruction (see [11]). Formative assessment is largely lacking in the traditional approach to engineering education, but is strongly emphasized in our implementation of challenge-based instruction. We have implemented formative

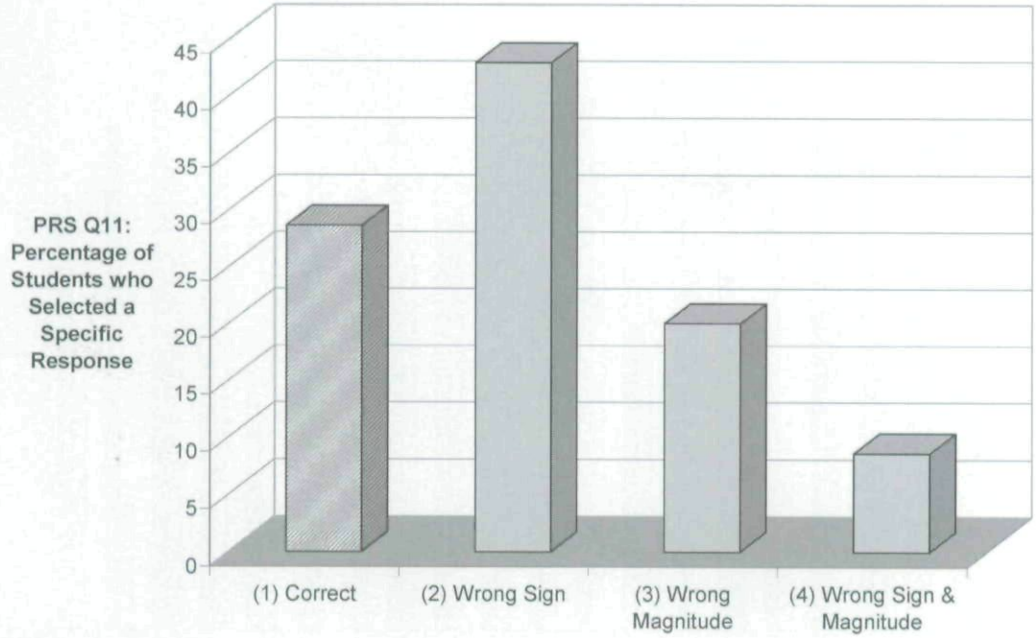

Figure 3b. Student response to the PRS question in Fig 3a. Only 28.6 percent of the class provided the correct response (#1).

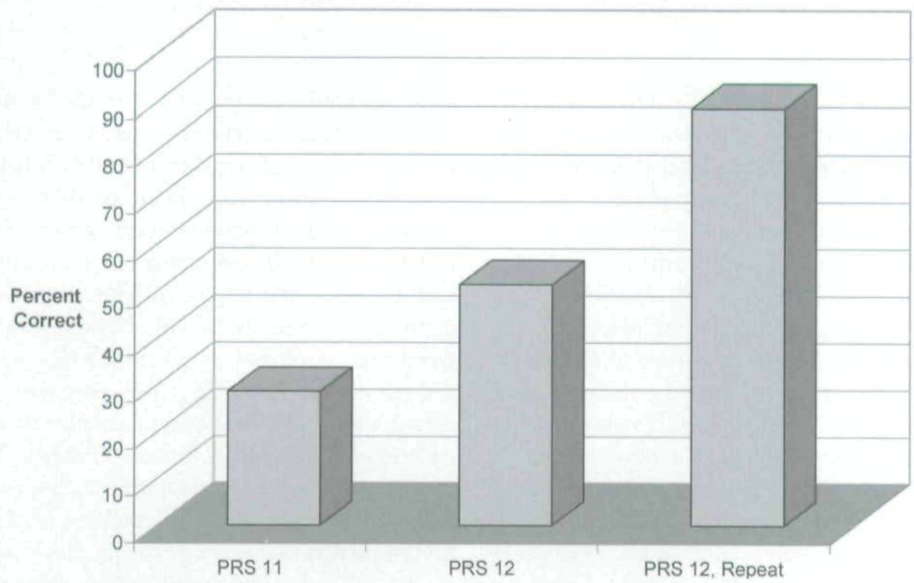

Figure 3c. The percentage of students correctly answering the PRS question in Fig 3a is shown by the first bar (PRS 11). The conventions were explained again and a similar PRS question asked (PRS 12). Since only half the class understood the conventions, they were explained a third time and PRS 12 was asked a second time.

assessments both in the classroom with PRS to monitor students' conceptual understanding in and out of class with CAPE/eLMS assessment modules that provide practice with feedback on fundamental procedures like vector operations and free body diagram construction.

CCS questions encourage students to review important concepts that have been recently introduced in the class and require students to make decisions based on the information at hand. Students report that the CCS system encourages them to be more attentive as the class proceeds, and the CCS questions stimulate them to ask questions on concepts they missed. As the semester progresses they become less inhibited, come to realize that they are not always right, and take some comfort in noticing that others in the class have trouble with the material as well. This provides some motivation for students to talk with each other during in-class brainstorming sessions. Most importantly, though, a CCS provides an opportunity for students to evaluate their understanding of new material immediately after it is presented to them: a classic application of formative assessment.

A significant bonus of a CCS is the immediate feedback available to an instructor. Students do not always interpret information that is presented in the classroom the way the instructor intended. It is sometimes stunning to find that more than half the class entirely

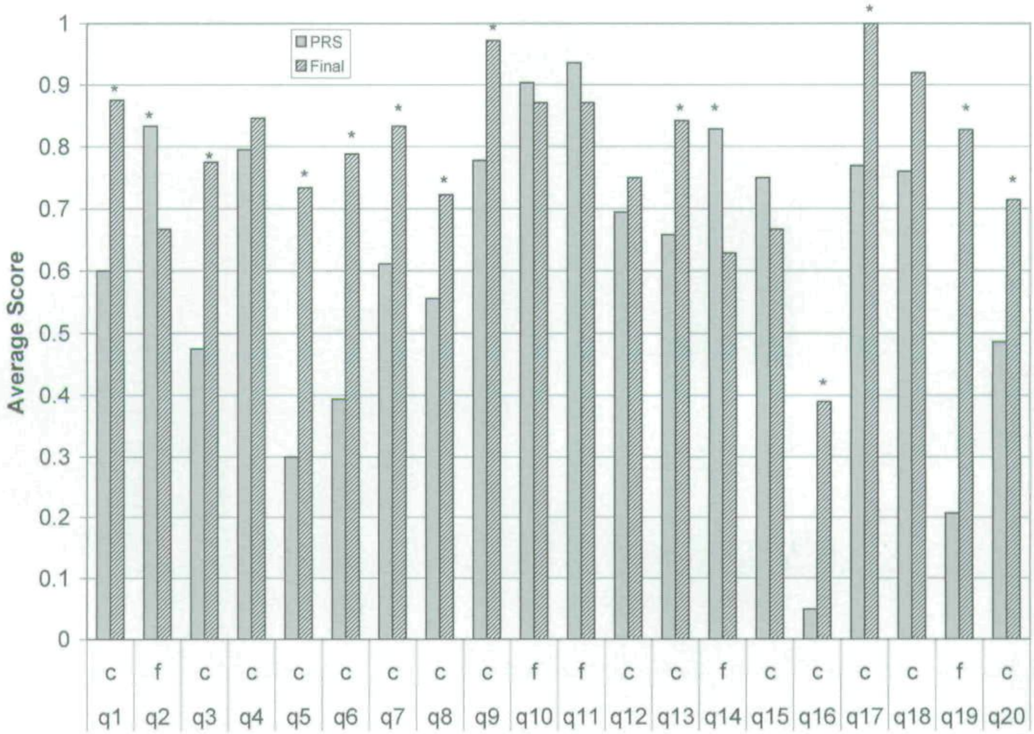

*Figure 4. Comparison of student responses in class vs. responses on final exam for twenty PRS questions. The row above each question number indicates if the question was primarily factual (f) or conceptual (c) in nature. *$p < 0.05$ by paired t-test.*

misunderstood a concept that was introduced no more than five minutes earlier. There is little that can be gained in moving forward with a new concept if the last one was misunderstood by a large percentage of the class. Difficult concepts sometimes need to be reviewed once or twice before moving on. Instructors must be prepared to suspend their plan for the remainder of the class period in favor of guiding class discussion following a CCS question or clarifying a concept by way of introducing additional examples.

Sometimes the CCS helps the instructor discover that a fundamental concept may have been underemphasized or even skipped. In one session, 60 percent of the class missed a CCS question asking them to identify the correct free body diagram associated with a section through the wrist joint. The students were asked to discuss their answer with others and the question was asked again. Not a single student answered it correctly the second time. A very lively discussion followed in which it became obvious that the students did not understand that active muscles can only pull, not push, on their surroundings. Somehow, that fundamental concept had not been properly emphasized, and the CCS can be credited for bringing this evidence to the instructor's attention.

An important component of an HPL classroom is its emphasis on learner-centeredness. Although students might do well in a traditional course, whether they come to class or not, this is less likely to apply to an HPL classroom. Our results show that active participation in the classroom, as measured with a CCS, is an important determinant of student performance in all aspects of an HPL course (Figure 5). In addition, results in Figure 4 support the findings of Brosvic et al. [12], who showed that immediate feedback is one of the active mechanisms for supporting students' retention of the fundamental concepts.

The particular technology used for a CCS is not important as long as the student responses can be presented anonymously and simultaneously, and the responses can be analyzed quickly by the instructor. Flash cards can be used as an effective CCS, since students cannot usually see the front of cards held up by other students [14, 26]. We chose a computer-controlled system because we were already using a computer projection system for other class materials and PRS offers the advantage of automatically compiling, sorting and displaying the responses. This allows students as well as the instructor to view the results. However, others have shown that when the use of flash cards and PDAs were compared, students showed no preference [26]. Also, post-analysis of results like those used in this study provide useful detailed data on the benefits of instruction for developing students' understanding. This information can help refine the instructional methods used in future courses (i.e., new computer tools designed in CAPE, or improved in-class learning activities including new questions using a CCS).

A CCS is simply one means for bringing formative feedback into a classroom. The use of other active leaning methods such as the Immediate Feedback Assessment Technique [12], brain storming, student-initiated questions, instructor-initiated questions, or any other instructor-guided discussion can also provide valuable formative feedback. All of these provide the student with the opportunity to become actively engaged in their own education, to become aware of what they know and what they do not know, and provides a forum for discussion and clarification. A CCS is ideally suited for this because an instructor can make students aware of their misconceptions through the application of well-designed questions.

How does an instructor go about designing good questions? Several good suggestions are provided by Beatty et al. [27]. Our approach has been to look at student performance on examinations, particularly final examinations, to see where students have trouble. Every concept has a number of misconceptions associated

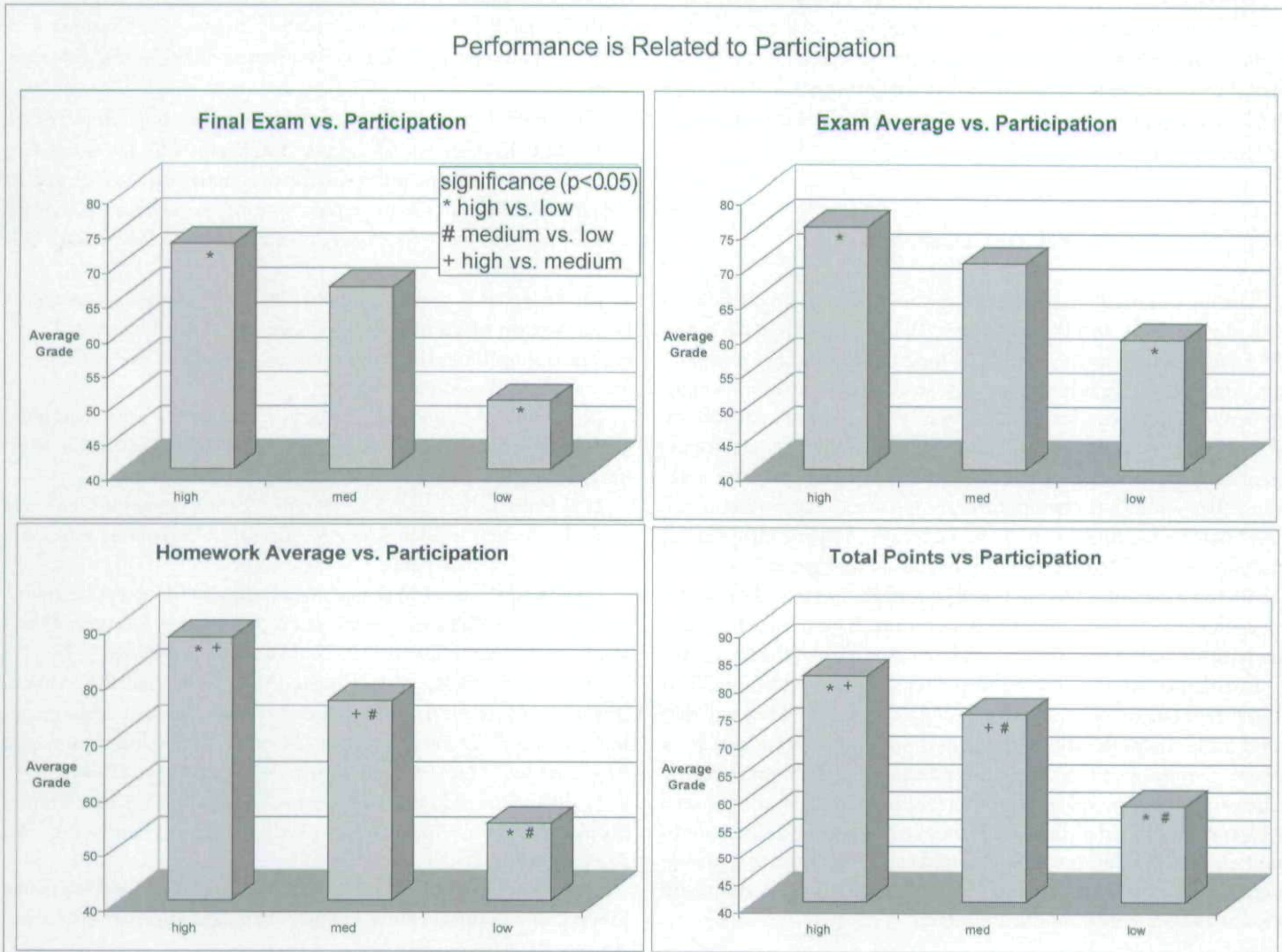

Figure 5. Student performance, determined in four ways (final exam, exam average, homework average, total points) was compared with student classroom participation, as determined from the number of PRS questions answered out of a total 94 asked over the course of the semester. The high participation group (n = 17) answered more than 89 percent of the questions, the medium participation group (n = 15) answered 68–89 percent of the questions and the low participation group (n = 14) answered 25–68 percent of the questions.

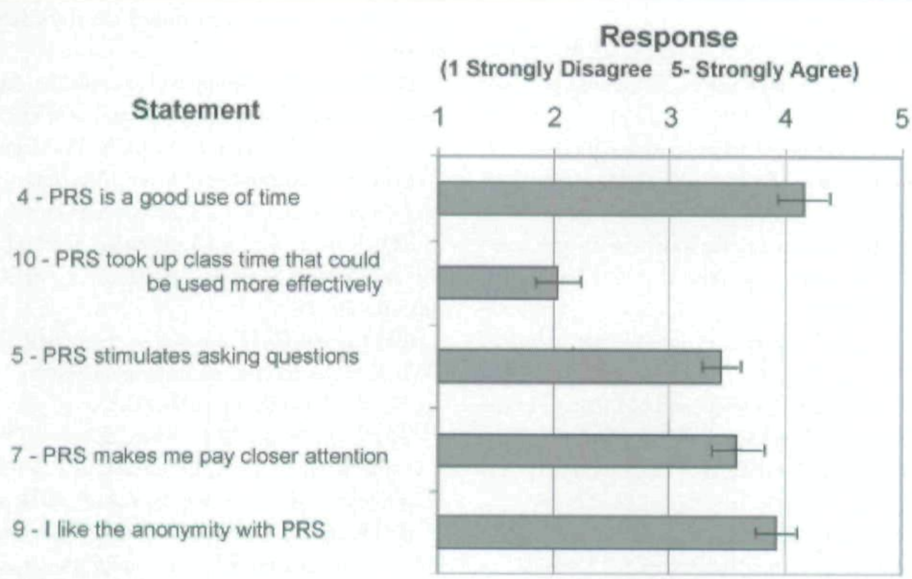

Figure 6. Student response to PRS.

with it. We try to design questions so that each of these misconceptions appears as a distracter in a multiple choice question. In that way we are reasonably confident that students will discover their own misconceptions and have an opportunity to correct them in a timely manner.

V. Conclusions

The use of formative assessment in the classroom is beneficial to both the students and the instructor. A CCS system such as the PRS can rapidly inform students of their understanding of important concepts. Since it is anonymous, student participation is high. Students tend to pay closer attention in the classroom, particularly after submitting incorrect answers. Although students are sometimes comforted to see that others are also making the same mistakes, they appreciate the opportunity to correct their misconceptions before moving on to new material. As time progresses, students tend to become less inhibited and more generative. They become more comfortable in asking questions in class. This active engagement with the content provides immediate feedback, which can have a significant impact on students' retention of the concepts.

Instructors can use student responses captured with a CCS to adjust their pace as they proceed through the course. They will discover areas where the students received poor preparation and areas where they received excellent preparation in their prerequisite courses. Instructors will become more aware of student misconceptions and conceptual difficulties as they add formative assessment to their classes. Finally, through the application of formative assessment, instructors may discover areas where their own classroom presentations are unclear or incomplete.

Acknowledgments

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