Professional Development of University Engineering Faculty through a Math-Science Partnership

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Abstract

A six-year partnership of nine school districts, the engineering and education colleges of a local university, and two industry partners was formed in the San José region to provide professional development for K-8 science teachers and university engineering faculty members. Professional development for the K-8 teachers was delivered via Summer Institutes, academic year workshops, and development of site-based study groups. This professional development work was led by trained K-8 professional developers in partnership with engineering faculty from the Institution of Higher Education partner. While working with the K-8 teachers, engineering faculty members also enhanced their pedagogical methods. Positive changes in teaching of engineering courses by the university faculty members were observed, including increased student-led inquiry, use of pre-assessment techniques, student-learning assessment, enhanced student probing, development of a university study-group to explore teaching of experimental design, and development of pedagogical content knowledge for basic engineering courses. Findings include identifying key elements of successful professional development programs, examples of the enhanced teaching practices of engineering faculty, development of a standard evaluation rubric for experimental design skills, development of educational standards for courses, and the development of preliminary concepts of pedagogical content knowledge related to engineering mechanics courses.

Introduction

Developing strong pedagogical skills in engineering faculty members is a critical component of enhancing engineering education. During the period 2003 to 2009, a National Science Foundation funded Math-Science Partnership[9] in the San José, California region invested time, money and effort in developing pedagogical skills in both K-8 educators and engineering faculty. The goals of the national initiative included the enhancement of educators at San José State University, the IHE partner (Institution of Higher Education)[9]. Initially, the Project Management team was hesitant in their expectations that the project would be able to contribute to this goal. However, as the project evolved, it became evident that the IHE faculty was implementing improved pedagogical practices in their teaching.

To achieve their objectives, the Partnership for Student Success in Science (PS^3) worked toward three goals, targeted primarily at the K-8 schools but related to work at the IHE:

1. Raise the overall science achievement in all PS^3 schools and narrow the achievement gap between lower-performing, high-priority schools and their higher performing counterparts.
2. Improve the capacity of pre-service and in-service teachers to deliver high quality science instruction.
3. Build the critical system supports necessary to help teachers achieve improved instruction and student success.

The project invested the majority of its resources into professional development of K-8 educators however, the involvement of engineering faculty as content experts in the professional development trainings over several years contributed to the additional outcome of strengthening their pedagogical skills.

The Partnership: The Partnership consisted of nine Silicon Valley school districts, San José State University's (SJSU) Colleges of Engineering and Education, and two local industry sponsors. Science teaching and learning, grades K-8, was improved through a continuum of training. Typical professional development for in-service teachers included one-week summer science institutes, one-day workshops, and personal mentoring.

The professional development for the K-8 teachers was designed and organized by master teachers from the districts. Engineering faculty members contributed to these professional development activities in multiple ways:

- Two faculty members were the STEM content experts at some of the summer institutes. This role required them to be actively engaged in the design and development of the institute as well as being an instructor during the week. Design and development required significant involvement over the four months prior to the institute while the goals of the training, the content emphasis and the pedagogical modeling were determined. Development and use of pre- and post-test assessment of the participants was designed, conducted and evaluated.
- The four faculty members attended and assisted with many of the one-day workshops. During these workshops, the IHE participant usually did not have a formal role in the professional development but served as a resource to the master trainers. These informal interactions allowed the IHE participants to discuss educational issues face-to-face, mentor individual educators, and observe successful pedagogical models.
- One IHE faculty member worked one-on-one with several teachers in drafting funding proposals to collect resources for the K-8 classroom. Teachers had limited prior experience on writing successful funding proposals and working with the engineering faculty members they were given support to define need and craft a successful proposal for sponsoring agencies.
- Engineering faculty partners were also involved with the overall project management, the evaluation of assessed data, the presentation of findings at various conferences, and the problem solving sessions used to adjust the project progress. Working as a member of the project management team involved in-depth discussion with educational researchers, allowing a very insightful introduction into large-scale evaluation and reform. In addition, this discussion provided resources such as research-rich teaching evaluation methodologies, nationally developed learning assessment tools, and participation at national science education reform trainings.

Reaching the Project Goals

The project had significant impact on the pedagogical skills and methods used by the engineering faculty. The Project Management team had expected that impact on IHE teaching practices would be limited, particularly considering that the focus on the K-8 science content would be tangential to the content expertise of the IHE faculty. However, expertise in content does not necessitate expertise in pedagogical skills, and while the IHE faculty involved in the project all had prior training and interest in developing strong pedagogical skills, it was observed that pedagogical expertise of the K-8 teachers transferred to the engineering faculty in both formal and informal means.

The engineering faculty partners were motivated to improve their pedagogical skills for both informal and formal reasons. Informally, the four faculty members felt that they needed to be the best instructors they could be to allow their students to achieve the defined educational outcomes of their classes. Formally, the need to meet ABET assessment requirements[1] was a strong motivator for the engineering college to strengthen the use of student achievement data collection, analysis of results, and implementation of improved instruction. Initially, the project envisioned a series of pedagogical workshops to be held at San José State. The goal was to develop and deliver a two-hour workshop each semester over the life of the project. The first of these workshops was held in Fall 2004 and provided guidance on the Inquiry Spectrum, the variation of learning environments from direct instruction to student defined inquiry. While the workshop was successful and attracted approximately 25 IHE instructors and resulted in increased use of inquiry and student-led discovery in several of the mechanical and aerospace engineering courses[3], the Project Management team subsequently refined their work plan. An underlying concept governing the Project Management decisions was that professional development would generally require about 100 hours of training to make notable changes in classroom practice. The IHE workshop strategy would have only provided about ten hours of training over several years and even when combined with a comparable amount of time for individual reflection, would have resulted in far less than this 100-hour threshold. Thus, the Project Management team in consultation with the IHE college administration determined that a wiser investment of their limited resources would be to strengthen the skills of the engineering faculty who were directly involved in the project, and having that enhancement transfer to other members of the college through peer-to-peer interaction.

Over the course of the project, changes in pedagogical skills of the engineering faculty were observed[2, 3, 6, 7]:

1. Use of pre-test evaluations to monitor student skills prior to instruction.
2. Improved use of data collection and evaluation of student learning.
3. Changes in educator perception of teaching skills and classroom culture.
4. Use of professional study groups for development of rubrics to evaluate student skills quantitatively suitable for use in a wide variety of courses.
5. Conversion of classroom instruction from a teacher-centered to a learner-centered environment.
6. Development of pedagogical content knowledge (PCK) of engineering curriculum.

Pre-Testing: Improved use of pre-test evaluation of student skills were implemented into the teaching of two engineering mechanics courses by one of the IHE faculty participants. A standard method of evaluation was developed for the beginning of the semester by selecting a portion of the nationally developed Force Concept Inventory[5] instrument. Figure 1 provides a summary of the student performance on different questions of that assessment instrument.

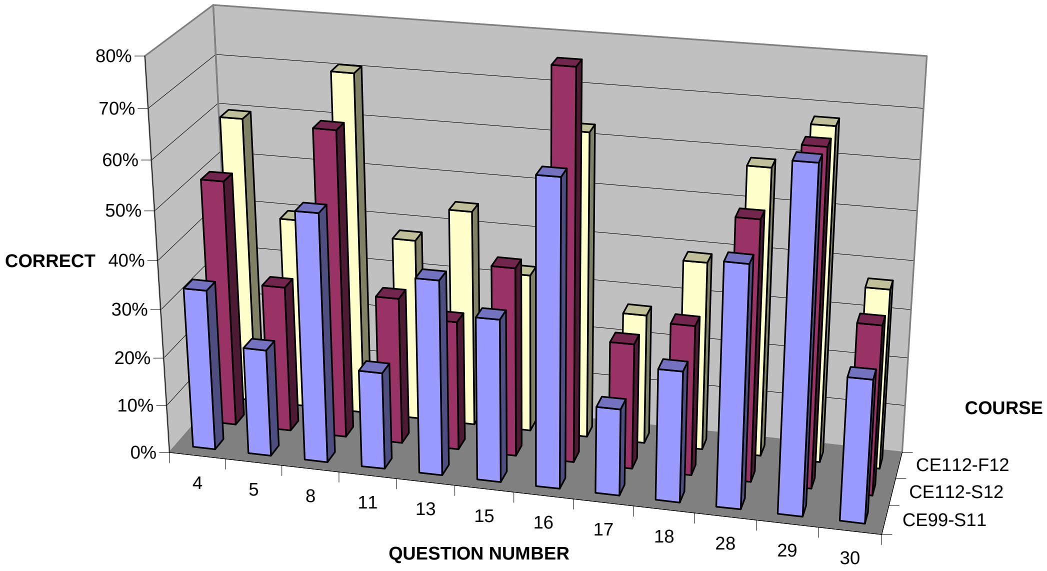

Figure 1. Student Performance on Force Concept Inventory Pre-Test Evaluation

Pre- and post testing is used for course outcomes assessment in technical writing, a required course for all engineering students[7]. In this course, the pre-test is a standardized writing skills test (WST) administered by the university to determine if students have adequate grammar and writing skills to be successful in the technical writing course. Students who earn below a 6 (on a 12-points scale) on the essay must take the test again and are offered several options to remediate their grammar and writing deficiencies. At the end of the course students complete a similar prompt-driven essay that is scored by using the same rubric. Students who did not earn at least a 6 must retake the technical writing course. A comparison of scores on the pre- and post-tests is used to evaluate the effectiveness of the course in achieving its stated learning outcomes. Figure 2 shows the average gains from pre-test to post-test. Students with lower pre-test scores (6 and 7) show the greatest gain.

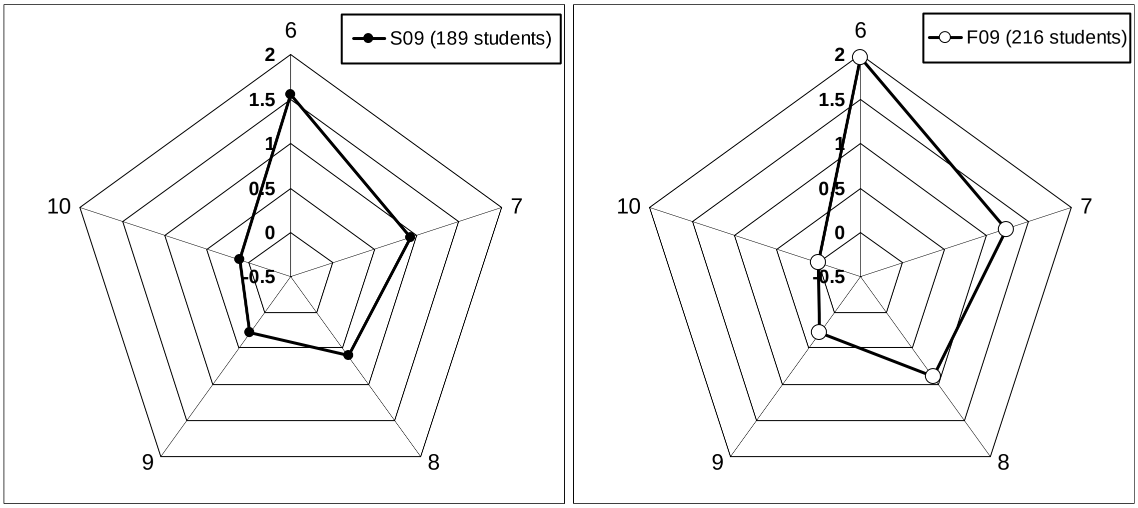

Figure 2. Gains on technical writing essay. The spokes represent the score on the pre-test (passing scores range from 6 to 12). The concentric pentagons represent the average gain[7].

Data Collection and Analysis: Engineering faculty members are very familiar with collection and evaluation of data due to their content research backgrounds. However, they usually have limited experience with comparable data evaluation in monitoring teaching skills. While interacting with a wide spectrum of educators during the project, aspects of data collection were noted. The use of research-based evaluative techniques during the K-8 professional development (Love, 2002), educated the IHE partners about formal methods of processing educational data. Specifically, aspects of this data processing for use in the ABET process were noted:

- The commonality of assessment processes to collect too much data in a form that is not conducive to evaluating the impact of individual enhancements.
- The limitations of data to capture the multiple influences on a student's ability to complete a task.
- The advantages of longitudinal tracking of student success as opposed to the evaluation of course performance by different cohorts of students.
- The statistical challenge of collecting enough data to establish direct correlations between student achievement and instructional practice.

Love[8] discussed the evolutionary stages of assessment processes. She also provides guidance on the usefulness of data-driven dialog. Of particular interest to the IHE partners were these points from her guideline:

- Data can help evaluate program effectiveness.
- Data can provide feedback to teachers and administrators.
- Data can prevent overreliance on standardized tests. Some civil engineering programs have tried to use the EIT exam results as a means of evaluating engineering education success. Love clarifies that while these results are useful in the assessment process, they are limited in their ability to identify learning weaknesses.
- Data can prevent one-size-fits-all solutions. While certain aspects of teaching skills may be easily transferred across universities, many meaningful enhancements must be developed locally to reflect the needs and resources of a specific course.

Love also discusses concerns about methods of using data. She warns against using data to identify poor teachers. She also warns about implementing high stakes requirements prematurely, such as having a certain performance on an assessment required for graduation.

Learning the limitations of data analysis was an important professional development outcome for the IHE faculty. An example of data use during the project was the tracking of the student achievement of grade 8 students. Sample sizes of approximately 7000 students per year were not large enough to statistically observe relationships between several factors evaluated. Since engineering colleges do not approach these numbers of students, the outcome of the evaluation was that assessment data should monitor longitudinal trends rather than specific point-in-time assessments. For example, a goal of the college was to see if modifications to a prerequisite would result in improved student performance in the subsequent course. The faculty found several factors limiting the likelihood of seeing a statistical verification of the impact of this change. First is the issue of non-uniform assessment instruments. Data could be collected in the prerequisite technical writing course on a student writing assignment evaluated on a 12-point scale and in the subsequent course student performance on lab write-ups could be evaluated on a different 6-point scale, thus limiting the accuracy of evaluation. Second, the evaluated population was small, approximately 150 students taking the subsequent course annually. Third was the issue of an unbiased control group. Many students of the benchmark control group already had taken the pre-requisite course prior to it being a required pre-requisite. Thus there was no control group available in which all of the students had not taken technical writing. With these limiting factors, it was unlikely to expect that a statistically valid improvement would be noted; however, tracing trends in student performance over several years may support the validity of the change. Thus, understanding the limitations of assessment data was a critical knowledge gain for educators.

A second example of data use related to considering student achievement in mechanics related to their understanding of Newton's Laws of Motion. As an initial evaluation, student grades in the mechanics course were compared with how they performed on the Force Concept Inventory[5] at the beginning of the course. Figure 3 is a comparison of that data. The graph shows a small positive correlation exists, although perhaps weaker than one might expect. Figure 3 considers a population of 82 students over two semesters. More data will be added as more courses are evaluated. Perhaps as the sample population increases, the findings will be more definitive.

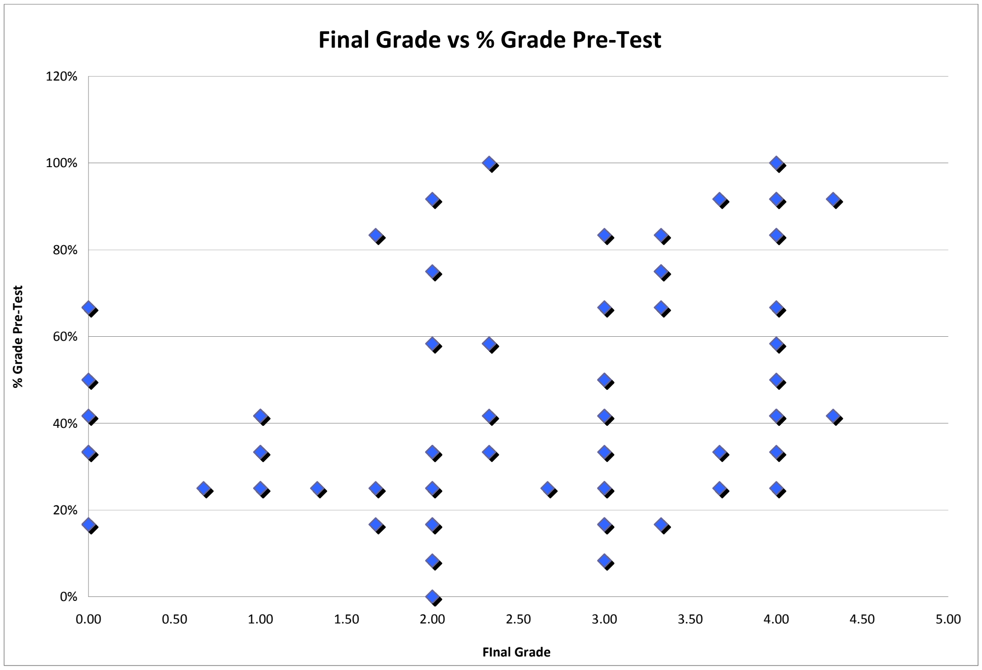

Figure 3. Correlation between Pre-Knowledge of Newton's Laws and Course Grade (A=4.00) in Mechanics of Materials

University Faculty Study Group: The project used study groups as a means of providing professional development to teachers at the middle schools. Study groups were developed for the middle schools following the Nancy Love[8] model. For the IHE partner, a study group was formed by the four SJSU engineering faculty to address an issue common to all faculty in the College of Engineering, assessment of ABET outcomes. They focused on ABET outcome 3b "an ability to design experiments." During AY06/07, the faculty met on a weekly basis to define the pedagogical issues, review the published literature, determine the steps in the design of an experiment, and create a rubric, test it, and refine it. The resulting rubric for design of experiment was documented in an article[2] and shared with faculty at other universities as a workshop at the 2007 Frontiers in Education (FIE) Conference.

The study group was a unique and powerful experience. The four faculty members were from different engineering disciplines and did not teach the same courses. However, they quickly discovered that they were all struggling with the same issues related to moving from cookbook to student-designed experiments. Initially, members of the study group identified relevant literature, which everyone reviewed and then discussed at the weekly meetings. The literature review served as a basis for defining the steps of a design of experiment. In particular two faculty members had already done some preliminary thinking about the design of experiments steps and had introduced some adjustments to their laboratory courses[3, 6]. As the group moved into the phase of formalizing a definition for these steps, each member shared what they did in their own classes. Group members critiqued each other's laboratory assignments and had lively discussions about what really required students to "design" their experiments. Many discussions revolved around levels of proficiency for the rubric. For example for the "select the proper range of independent variables" step, the group discussed at great length the difference between "reasonable" and "optimal" ranges, giving examples from their own experiences. The resulting rubric was clearer and more generally applicable because of the input of this multidisciplinary group. Having the opportunity to discuss course activities in such a supportive and open environment was extremely gratifying and productive.

Changes in Classroom Instruction: Classroom instruction was altered by multiple faculty members after being exposed to enhanced instructional models used by the K-8 master teachers. The use of probing questions by the course instructor during both class period and office hours deepened student understanding. Engineering instructors became more aware of the importance of asking questions of students rather than give direct answers and thus used this technique more frequently and more effectively than previously. These questions are intended to require the student to self-reflect on the 'correctness' of their thinking and see if their thoughts are applicable to other situations. This questioning technique has replaced the instructor's natural tendency to tell the student the correct answer to a question, or to immediately point out an error in the student's reasoning. The goal of the probing question method was to improve a student's ability to reflect on their thinking and self-adjust their conceptual understanding.

Evaluating student knowledge according to conceptual understanding was another alteration in instructional methods. Prior to the interaction with the K-8 educators, the engineering faculty members' often evaluated student using a detail-oriented evaluation. For example, points on an exam calculation problem were given based upon each variable in the calculation being correct or not. While being involved with the project, faculty members began to take a more holistic approach to exam problems, both in the way they were written and the way they were scored. The goal was to develop exam problems that focused less on computation and more on concepts. Grading then moved toward evaluating if the student understood the underlying concept and was able or unable to execute it, and to understand if the student failed to even understand the concept being applied. With computationally heavy problems this type of conceptual evaluation can be lost.

Improved Pedagogical Content Knowledge: Expanding the concept of Pedagogical Content Knowledge (PDK)^4 and applying it to engineering education was seen as a good investment for faculty time. The ability of engineering students to draw complete and correct Free Body Diagrams (FBD) was seen as a critical skill. Engineering students in the mechanics courses (Statics, Mechanics of Materials, Dynamics, and Fluid Mechanics) frequently use equilibrium concepts to solve engineering problems. The ability to correctly draw a FBD would allow students to perform better in multiple classes, but faculty instructors often commiserate over student's weakness in this skill. To improve on the instruction of this skill, one faculty member made this a key goal for enhancement of his mechanics courses.

To strengthen student skill in drawing FBD, the following steps are being pursued:
1. Clearly identify the characteristics of a good FBD.
2. Distinguish conceptual and application level skills required.
3. Develop an evaluative rubric to consistently grade and monitor student progress.
4. Develop specific assessment tools to monitor student performance.
5. Enhance lectures and instructional materials.
6. Track changes in student performance over time.

Two courses have received the initial attention on this topic, Statics and Mechanics of Materials. One instructor teaches sections of each topic.

Multiple phases of development of this PDK were undertaken. First, five main characteristics of good FBD were defined and emphasized to students. The complete diagram was to include:
1. A neat and roughly scaled sketch of the object isolated from the environment.
2. All known forces with magnitudes, units and sense shown in vector format.
3. All unknown forces with symbol and assumed sense shown in vector format.
4. All critical dimensions required for equilibrium calculations.
5. A coordinate system.

The second phase was to distinguish the skills between conceptual (identifying applied forces and moments, isolating an object, representing reactions as unknown quantities, identifying and resolving critical dimensions) and implementational (adding coordinate system for clarification, units, neatness). The third phase was to develop the rubric listed in Table 1. For the fourth phase, one exam problem of each exam (two midterms and a final) required the students to explicitly draw a complete FBD needed for the problem. This FBD was assigned points and graded separately from the main problem; i.e. students might correctly calculate the numeric solution to the problem but if the FBD diagram was incorrect they would not earn full credit for the problem. While students are encouraged to draw FBD for all problems on exams, FBD are not always required to allow students flexibility in their time management during the exam. The fifth phase of improving instructional practice continues, but as a start, the five FBD characteristics are recited by the class several times during the semester and students are expected to have memorized the items prior to the first midterm. As a visual clue, the instructor uses five fingers to indicate the five characteristics in a consistent order to improve student retention abilities. Table 2 lists some observed trends in student performance.

Table 1. Rubric for Free Body Diagrams

Score	Performance	Examples
100%	Solution is correct and complete	Object cut loose from the environment; known forces w/magnitude, sense and units; unknown forces w/symbol and assumed direction; critical dimensions to solve for equilibrium; coordinate system
90%	One minor error	Solution is missing or has incorrect information for one of the following: coordinate system, units on known forces, units on dimensions, symbols for unknown forces
70%	More than one minor error	Solution is missing or has incorrect information for more than one of the following: coordinate system, units on known forces, units on dimensions, symbols for unknown forces
50%	Conceptually correct	FBD contains all forces/moments acting on the object and no more. Sense and magnitude of known forces may be incorrect.
20%	Knowledgeable attempt	FBD contain the majority of forces/moments acting on the object, but the sense or magnitude may be incorrect or there are no more than two nonexistent forces/moments shown.
0%	Minimal solution provided but provided material is conceptually correct.	Page is essentially blank or there is a minority of actual forces/moments shown or more than two nonexistent forces/moments shown.
-20%	Student writes something on exam solution that is conceptually incorrect.	Acceleration or mass values are identified as a force.

Another aspect of PDK is defining why students produce the incorrect result. Preliminary evaluation of the results from the Force Concept Inventory has been conducted. The poorest performance has been on Question 17, related to the relationship of the upward force of the cable on an elevator to the downward force of gravity when the car is traveling upward at a constant speed. Barely 20% of the students correctly identify that the forces are equal while the vast majority expect the upward force to be larger. Questions 15 and 16 both relate to a scenario where a small car is pushing a heavy truck. Both ask for the relationship between the force of the truck on the car and the force of the car on the truck. Students consistently do better on Question 16 where the two vehicles are traveling at a constant rate, but are more likely to not realize the two forces are equal when Question 15 asks them about a situation where the two vehicles are speeding up. Another early observation of the instructor was the very limited use of diagrams by students to make judgments about the correct answers. The assessment is multiple choice and does not require calculation, but consistently, very few students make any type of force drawing on their paper as they try to solve the questions.

Table 2. Trends in Drawing Free Body Diagrams

Term	Observation	Remarks
Spring 2010 Statics Course	60%	Average score on Final Exam for problem requesting students to draw a FBD.
Spring 2012 Mechanics of Materials Course	79%	Average score on Final Exam for problem requesting students to draw a FBD.
Fall 2012 Mechanics of Materials Course	82%	Average score on Final Exam for problem requesting students to draw a FBD.
Fall 2012 Mechanics of Materials Course	60%	Percentage of students who drew a FBD on another problem of the exam to solve a complex stress analysis problem (axial, bending and shear).

Discussion

An important outcome of this project is the two-way professional development that occurs when K-12 and higher education institutions partner to improve student achievement. A typical model is one in which the IHE is assigned the role as the provider and the K-12 institution the receiver. But in fact, both partners can and do learn from each other. Based upon the PS^3 project's past work, review of published research and personal experience, the following are designated as key elements for a project of this type to succeed:

1. Focus professional development on Early Adopters. In any faculty group, some instructors are receptive to trying new pedagogical methods and adapting their courses, and other members are not. One administrative need, possibly even more acute at the IHE than the K-8 level, is a way to identify, support, and reward the Early Adopters. Educational reform will start with the Early Adopters, expand with the sharing of those changes with other instructors, and likely skip over the more incalcitrant members of the faculty.
2. Support a highly motivated, visionary Project Director with commitment to project success. It is critical that the Project Director have sufficient time and resources to build alliances, communicate project work, coordinate meetings, and review project success. The authors believe that one of the prime reasons for the success of the project was a highly-capable Project Director, who was provided adequate resources to devote her talents full-time to this project.
3. Assign professional development responsibilities to K-12 Content Resource Teachers. Content Resource Teachers designed and delivered professional development through formal workshops, one-on-one mentoring, and collaborative team support. The project's resources allowed the content teachers be released from classroom teaching assignments during the project. This allowed for the team of resource teachers to meet with local teachers, meet as a team to develop and deliver high-quality professional development, review relevant research and strengthen their own content and pedagogical skills.
4. Support site-based Collaborative Teams of teachers. New strategies will be reinforced and therefore more rapidly institutionalized when there is a critical mass of content-specific educators at an individual school site who have a self-motivation for school reform, student success, and collaborative spirit. A minimum of 50% of content-specific instructors at a school are envisioned for a Collaborative Team for each participating grade level.

5. Enlist District/Administrative support. Leadership, administrative, and financial support from participating school districts is essential to motivate teacher participation, recognize local achievement, assist in project guidance, and provide instructional materials.
6. Provide stipends for teacher participants. Financial stipends are critical to attract teachers to professional development, reward them for their time commitment, and honor their work for school and student improvement.

Acknowledgements

This material is based upon work supported by the National Science Foundation through Cooperative Agreement No. EHR-0315041. Additional support was provided by the San José State College of Engineering. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation or San José State University.

References

1. ABET. (2012). *Criteria for Accrediting Engineering Programs 2013-2014*. Engineering Accreditation Commission. Baltimore, Md. Retrieved Nov. 11, 2012 from http://www.abet.org/accreditation-criteria-policies-documents/
2. Anagnos, T., Komives, C., Mourtos, N., & McMullin, K. (2007). Evaluating Student Mastery of Design of Experiment, *37th ASEE Frontiers in Education Conf.*, Milwuakee, WI.
3. Du, W. Y., Furman, B. J., & Mourtos, N. J. (2005). On the ability to design engineering experiments, *8th UICEE Annual Conference on Engineering Education*, Kingston, Jamaica.
4. Gess-Newsome, J., & Lederman, N. (1999). *Examining Pedagogical Content Knowledge*. Boston: Kluwer Publishing.
5. Halloun, Ibrahim & Hestenes, David. (1985). The initial knowledge state of college physics students. *American Journal of Physics*, Volume 53 (11), 1143-1055.
6. Komives, C., Mourtos, N. Anagnos, T., & McMullin, K. (2006). Enhancing Inquiry Skills in Engineering through a University-School District Partnership, *Proc. 9th Int. Conf. Eng. Ed.*, San Juan, Puerto Rico.
7. Linsdell, J., & Anagnos, T. (2011) Motivating Technical Writing through Study of the Environment, *J. Professional Issues in Eng. Ed. and Practice*, ASCE, V137, 20-27.
8. Love, Nancy. (2002). *Using Data/ Getting Results: A Practical Guide for School Improvement in Mathematics and Science*. Christopher-Gordon Publishers, Inc., Norwood, MA.
9. National Science Foundation (2013). Math and Science Partnership. http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5756&org=ehr