Implementation of Interdisciplinary Group Learning and Peer Assessment in a Nanotechnology Engineering Course

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Abstract

Nanotechnology is an inherently interdisciplinary field that has generated significant scientific and engineering interest in recent years. In an effort to convey the excitement and opportunities surrounding this discipline to senior undergraduate students and junior graduate students, a nanotechnology engineering course has been developed in the Department of Materials Science and Engineering at Northwestern University over the past two years. This paper examines the unique challenges facing educators in this dynamic, emerging field and describes an approach for the design of a nanotechnology engineering course employing the non-traditional pedagogical practices of collaborative group learning, interdisciplinary learning, problem-based learning, and peer assessment. Utilizing the same nanotechnology course given the year before as a historical control, analysis of the difference between measures of student performance and student experience over the two years indicates that these practices are successful and provide an educationally informed template for other newly developed engineering courses.

I. Introduction

President William J. Clinton announced the National Nanotechnology Initiative (NNI) to the public in January 2000 [1]. The NNI provides funds to a diverse range of federal funding agencies including the National Science Foundation, the National Institutes of Health, the Department of Defense, and the Department of Energy to pursue nanotechnology related research and education that will help satisfy the economic, health, national security, and energy needs of the 21st century [2]. In response to the perceived impact of the NNI, the National Science Foundation estimates that 2 million workers will be needed worldwide in nanotechnology in 10–15 years [3]. Consequently, educators have begun to organize engineering courses and curricula designed to train this new workforce [4]. Concurrently, engineering education has been undergoing a shift from passive, principle-based learning to active, problem-based learning [5]. In this paper, we describe our efforts to implement the latter approach in an interdisciplinary nanotechnology engineering course at Northwestern University.

Like many recent technological developments, nanotechnology exists at the interface among traditionally defined disciplines. Consequently, students who will enjoy successful nanotechnology careers must effectively communicate their specific knowledge and perspective with experts from other fields in the context of interdisciplinary problems. The nanotechnology engineering course described in this paper attempts to develop these skills through interdisciplinary student-centered group work. Although the concepts of cooperative learning [6] and problem-based learning [7] have been described previously in the context of undergraduate engineering courses, this paper describes how these ideas can be effectively applied to nanotechnology engineering education.

A major issue confronting the rapidly advancing field of nanotechnology is that many of the exciting experimental results and predictions for the future have not been rigorously proven or independently reproduced. For example, contradictory articles published in a recent special issue of *Scientific American* [8, 9] on nanotechnology illustrate the controversial nature of ongoing nanotechnology research. The preponderance of misinformation in popular sources of nanotechnology information has also led to significant misconceptions among students and the general public. Consequently, students seeking nanotechnology careers must also learn to critically evaluate current research and advances in nanotechnology to determine validity and rigor in today's scientific community. The nanotechnology engineering course developed specifically addresses these controversies through group activities that require students to perform critical evaluations of nanotechnology issues. Just as professionals are called upon to evaluate one another through peer review, this course uses peer assessment for assigned group activities so that students have the opportunity to critically evaluate each other.

Overall, the design of this course brings together a range of non-traditional pedagogical practices, including collaborative learning, problem-based learning, peer assessment, and an interdisciplinary approach to construct a learning environment in which students are not only exposed to the scientific and engineering issues surrounding nanotechnology but are also given the opportunity to develop interpersonal and critical evaluation skills necessary for effectively advancing this field into the 21st century.

II. COURSE DESCRIPTION AND OBJECTIVES

Materials Science and Engineering 395, "Nanomaterials," is an introduction to processing, structure, and properties of nanostructured materials (critical feature size $\leqslant 100$ nanometers). The course covers recent breakthroughs and assesses the ultimate impact of this burgeoning field. Specific nanofabrication topics include beam lithographies, epitaxy, self-assembly, biocatalytic synthesis, atom optics, scanning probe microscopy, and nanoelectromechanical systems (NEMS). These techniques have enabled the development of nanostructured polymers, semiconductors, superconductors, and organic materials. The unique electrical, mechanical, magnetic, and chemical properties that result from nanoscale structure are explored. Overall, the course examines how nanofabrication techniques can control the structure of materials at the nanometer length scale. This nanoscale structural control enables predictable control over size-dependent properties, which can be utilized in a variety of applications ranging from nanoelectronic circuitry to high strength nanocomposite materials.

This course is meant to serve as an overview of recent developments in nanoscale science and technology. While quantitative relationships are used and developed in the course, most equations are not derived from first principles due to time limitations. For those students who are interested in the detailed derivations, a subsequent graduate level course is available. However, for the undergraduate level course, conceptual understanding is emphasized and designed to be advanced to a level where the successful student can pick up a technical journal article and comprehend the scientific merit of a recent advance in nanotechnology. In an effort to aid other instructors who are interested in developing nanotechnology courses, a list of course resources has been supplied in Appendix A.

Nanomaterials was first taught at Northwestern University in the Spring 2001 Quarter. Senior-level undergraduates and junior-level graduate students from all engineering and science departments were invited to enroll in the class. Consistent with the interdisciplinary appeal of nanotechnology, the course attracted eight undergraduate students and nine graduate students from a variety of departments including electrical engineering, mechanical engineering, materials science, and chemistry. During the Spring 2001 Quarter, group activities were not assigned. Although interaction was encouraged among the students and the instructor, the class was largely taught with traditional lectures. Individual homework assignments challenged students to critically evaluate nanofabrication issues such as the relative merits of different lithographies for a given material system. The final project consisted of a written literature review and research proposal that was also presented orally in class. In addition, the final examination asked the students to apply their knowledge to a nanoelectronics or NEMS design problem.

The course and teacher evaluation survey conducted by Northwestern University at the end of the quarter showed that students were generally satisfied with the course. On a scale of 1 (low) to 6 (high), students rated the course between 4.6 and 4.9 on five items (see Figure 2). One student in particular commented, "This class is accessible to non-engineers/scientists as well, and I think those people can learn much, particularly because communication and creative thinking are emphasized." In response to the final research proposal, another student wrote, "It was a useful course that encouraged students to explore topics through research rather than textbook learning." These initial survey results indicated that pedagogical efforts to encourage critical and creative thinking were well received and valued by the students.

Consequently, the course objectives and pedagogy were substantially developed for the Spring 2002 Quarter to provide students with additional and richer opportunities to engage in activities that would stimulate creative and critical thinking in the field of nanotechnology. The new design was developed with respect to two key pedagogical frameworks. The first framework—a critical matrix of higher education learning environments [10]—concerns the scope of the learning objectives and the learning contexts addressed by the course. The second framework, constructive alignment [11], is concerned with the alignment of learning objectives, teaching strategies and student assessment at a deep or constructive (as opposed to reproductive) level of learning.

With respect to the first framework, the course learning objectives were expanded beyond the traditional content-based knowledge objectives to embrace the four distinct learning dimensions—intellectual, personal, social, and practical (see Table 1 below). While frequently overlooked in course development, these additional categories are of critical importance to overall student learning.

> "Traditional teaching has generally suffered from separating off the lecture and seminar room from the social dialogue and engagements of a concrete world; where human intellect functions within the rich and substantial context of social relationships and personal conceptions of who we are and what we want to be. These broader issues of personal and occupational identity can dramatically affect our learning in all contexts...They frequently become the most important and relevant components to student success." [10]

In addition to expanding the dimensions of the learning objectives addressed by the course, the formal intellectual objectives were

Practices	**Learning Objectives (Categories)**			
	Intellectual	***Practical***	***Personal***	***Social***
Collaborative Learning	√		√	√
Interdisciplinary Learning	√			√
Problem-based Learning	√	√	√	
Peer Assessment		√	√	√

Table 1. Aligning learning objectives and pedagogical practices.

refocused to more substantially address the higher levels of Bloom's taxonomy of educational objectives [12]. These objectives include:

(1) Students will explain how the structure of materials can be controlled down to the nanometer scale through various processing methods.
(2) Students will compare and contrast structure-property relationships at the nanoscale.
(3) Students will assess applications involving nanostructured materials.
(4) Students will develop and use effective interdisciplinary communication skills.
(5) Students will critically evaluate topics in the emerging field of nanomaterials (i.e., distinguish progress from hype).

The additional three categories of social, personal, and practical learning objectives articulated in the "Nanomaterials" course design include the following:

(1) Students will gain a sense of ownership of the course content and collaborative projects.
(2) Students will engage in both self- and peer-assessment.
(3) Students will collaborate with peers to accomplish course assignments.
(4) Students will lead discussions and planning of collaborative projects.
(5) Students will collaborate with peers from other disciplines as well as from their own discipline.
(6) Students will gain confidence as students and professionals in the study and evaluation of research and advances in nanotechnology.

The course design was also informed by three learning contexts which the matrix describes: (i) contexts which provide support; primarily conveyed by the teacher; (ii) contexts which encourage independence; increasingly managed by the individual student; and (iii) contexts which develop the interpersonal; equitably shared among students and teacher [10]. An important challenge in the design of the overall learning environment consists of determining the particular equilibrium among these contexts. The design of the "Nanomaterials" course, derived from the learning objectives, included a combination of the three contexts, but emphasized the interpersonal context more fully than is traditionally the case. One of the main reasons for this emphasis stems from the interdisciplinary nature of the subject and the interdisciplinary backgrounds of the students taking the course. It was essential that the students develop the interpersonal structures to enable them to effectively share their diverse disciplinary expertise.

The second pedagogical framework employed in the redesign of the course focused on aligning the range of new learning objectives and contexts with both the teaching practices employed in the course and the procedures for assessing the students. Although a number of the intellectual objectives, mainly concerned with the knowledge content of the course, might have been effectively addressed using interactive lectures, the majority of the other course objectives required a more inventive approach to teaching. The strategy chosen to achieve the broad range of objectives described above focused on four key pedagogical practices found in the literature on teaching and learning in higher education: collaborative learning, interdisciplinary learning, problem-based learning, and peer assessment.

In collaborative learning practices, student learning is achieved as part of the collaborative efforts of a group to extend the knowledge and apply it to specific problems. The learning is often superior to those of students working in competitive and individualistic settings [13]. Interdisciplinary learning provides the opportunity for students from a range of appropriate disciplines to engage in learning activities which are essentially new and fully interdisciplinary in nature, with potential for developing more interesting problems and assignments, and more critical, original and diverse approaches to solving problems [14]. Problem-based learning begins with real-life problems, intended to emphasize the relevance of the course content for students, stimulate their problem solving skills and enhance their desire to continue learning [10]. Peer assessment involves students in the process of critically assessing their peers' projects and learning. It helps them develop a sense of ownership of their learning and enhances their ability to critically evaluate their own learning [15].

Different teaching strategies provide the opportunity for employing one or more of these pedagogical practices. Table 1 indicates the categories of learning objectives that the individual practices are intended to address.

The pedagogical approach described in this paper is innovative in specifying (i) objectives in four rarely integrated categories of learning outcomes, (ii) alignment of these objectives with non-traditional practices addressing the core outcomes of each category, and (iii) alignment of the learning objectives and practices with a range of appropriate assessment methods.

III. COURSE IMPLEMENTATION

In the Spring 2002 Quarter, Nanomaterials attracted 19 students including three auditors (nine undergraduates and ten graduate students) from five departments (Materials Science and Engineering, Chemical Engineering, Electrical and Computer Engineering, Mechanical Engineering, and Chemistry). The course met for 90 minutes twice per week for ten weeks. Course notes were posted on the Internet so that students could look over the material before it was presented in class. In a typical two week time period, three of the four classes were devoted to interactive lectures. The fourth class period was devoted to student presentations and peer assessment of group projects that were assigned in place of homework.

Throughout the quarter, four group projects were completed. Although the four group activities covered a variety of topics, they were all designed to induce communication and evaluation among team members. For example, the following is the project description for the first group activity on nanofabrication:

> All of the schemes for nanofabrication that we have discussed thus far in this course (i.e., Molecular Beam Epitaxy, Metal Organic Chemical Vapor Deposition, Deep Ultra Violet Photolithography, Extreme Ultra Violet Photolithography, X-ray Lithography, Ion Beam Lithography, and Electron Beam Lithography) require a significant capital investment (> $1 Million). For this activity, assume that your group represents an interdisciplinary committee of university faculty. This committee has been formed to evaluate the aforementioned nanofabrication approaches and recommend the purchase of one system to the university administration.

This activity required the students to not only learn the technical merits of each nanofabrication technique but also to consider the overall impact on the diverse range of departments within the university. This type of interdisciplinary decision-making was also present in the other assigned group activities throughout the quarter. Since different disciplines may have different opinions about the relative merits of these nanofabrication techniques, it was important that each group have representatives from a range of disciplines to ensure that an optimal choice was made for the overall benefit to the university. Consequently, for this and other group activities, the instructor chose groups that ensured interdisciplinary representation. To help with the selection of groups, the instructor asked all of the students at the start of the course to list: (1) year in school, (2) department affiliation, and (3) specialization. Based on this survey, the instructor assigned groups in a manner that maximized the diversity of disciplinary backgrounds, educational levels, and expertise. Throughout the quarter, the makeup of the groups was varied to ensure that students had the opportunity to work with a wide range of talent levels, work ethics, and personalities.

Three of the groups then executed the activity outside of class and reported their conclusions to the fourth group (designated as the evaluation committee) and the instructor during class. The teaching assistant chaired the evaluation committee, and helped it develop the criteria used to evaluate the peer presentations. The committee ultimately was expected to deliver a score between 1 and 100 to the course instructor. For the nanofabrication activity described above, the evaluation committee used the following weighted criteria: (a) Thoroughness—30 points, (b) Technical Accuracy—20 points, (c) Interdisciplinary Collaboration—15 points, (d) Clarity—10 points, (e) Persuasiveness—30 points. The committee assigned points according to their assessment scheme and wrote a brief report justifying their scores. This report was then delivered to the instructor. At this point, the instructor had the opportunity to adjust the grades if he felt that the evaluation committee had not performed a fair, objective, and quality assessment. Although this check on the evaluation committee was performed on all group activities, no grade adjustments were necessary by the instructor. Consequently, the group activity scores were 100 percent determined by peer assessment.

In a further effort to simulate reality, the evaluation committee's criteria were not explicitly revealed until all groups had presented their group activity in class. At the end of the class period, the evaluation committee was asked to stand up in front of the class and reveal their criteria to their peers. Furthermore, the written reports from the evaluation committee were delivered verbatim to the groups, following the check by the instructor. With this structure, the groups were encouraged to perform the highest quality work in an absolute sense rather than catering to a predetermined list of criteria. In addition, over the course of the quarter, all students were given an opportunity to serve on the evaluation committee, thus providing them with the experience of peer assessment and scrutiny that is commonplace among professional scientists and engineers.

Following the four group activities, the students were well positioned to execute the final project. The final project asked the students to propose a new, creative approach to a well-defined problem in the field of nanotechnology. The project was expected to justify the relevance of this problem, provide a literature review of related work, and clearly delineate the proposed approach. In an effort to provide practical, real world experience, the specific proposal guidelines were taken from the Nanoscale Exploratory Research and Nanoscale Interdisciplinary Research Team initiatives of the National Science Foundation [16]. These guidelines included a three-page preproposal that was submitted to the instructor in the middle of the quarter. The instructor provided formal preliminary feedback to the groups at that time. In addition to the written proposal, the students were asked to present their proposals to the instructor and their peers in class.

Since all students completed the final project, there was not a group specifically committed to developing an evaluation rubric. Instead, the evaluation criteria for the final project were modeled after the National Science Foundation [16], including a ranking of the intellectual merit and broader impacts of the proposed activities. Appendix B delineates the interpretation of the National Science Foundation criteria that was employed for the final project. To maintain consistency with the remainder of the course, these evaluation criteria were strongly correlated to the course objectives and desired learning outcomes. During the class presentations, students in the audience were asked to anonymously score each final project according to the National Science Foundation criteria. Because the peer assessment was less thorough in this case, the student-generated score contributed less to the final project grade than the group activities. The average score from this peer assessment made up 20 percent of the total score for the final project. The remainder of the final project grade was determined from the instructor's assessment of the final presentation (30 percent) and written proposal (50 percent).

The course concluded with a final examination that asked students to critically evaluate nanotechnology topics within the context of nanomaterials topics covered in the course. Questions on the final exam covered nanotechnology policy issues, nanoscale device design issues, and current limitations of nanocharacterization techniques. The final examination was taken individually by the students and graded exclusively by the instructor. The overall grade calculation is summarized in Table 2. Peer assessment comprised 46 percent of the total score for this course.

	(I) % of grade determined by peer assessment	**(II) % of overall course grade**	**(III) % of overall course grade determined by peer assessment = product of (I) and (II)**
Group Activities	100%	40%	40%
Final Project	20%	30%	6%
Final Exam	0%	30%	0%

Table 2. Role of peer assessment in grade calculation.

IV. METHODS OF EVALUATION

The evaluation methods of this study focused around two main sets of questions. The first was concerned with whether or not there was any significant change in student performance which we might attribute to the design of the new course, and the second was concerned with whether or not there were differences in the students' experience of the course that might be attributed to the redesign of the course. The corresponding nanotechnology course given the year before by the same instructor was employed as a historical control for the study.[1] It should be noted that the distribution of graduate and undergraduate students in the two instances of the course was similar, with a slightly higher percentage of graduate students participating in the earlier 2001 instance of the course. In 2001, nine of seventeen students (53 percent) were graduate students, and in 2002, seven of sixteen students (44 percent) were graduate students

A. Performance

For the purposes of this paper, it was decided that performance would be measured in terms of an analysis of the difference in individual project marks between the initial course offered in the spring of 2001 and the redesigned course offered in the spring of 2002. The other potential measures of performance were marks for the group activities, final exam and final grade. The measure of group activities was not used, as it was entirely determined through peer assessment; the student assessors by definition were different between the two years, limiting the reliability of the measure for comparison purposes. Final exam scores were also not used, as the questions on the two sets of exams were not constant between the two years. Finally, the course grade, 70 percent of which was comprised of group activity and final exam scores, was not deemed to be an appropriate measure. However, the project mark was chosen as the key measure for a number of reasons: (i) it provides a more valid measure of the range of the student learning outcomes stipulated by the course; indeed, in future course offerings, the final exam will be eliminated in favor of a higher weighting for the project; (ii) the assessment method remained constant and unchanged between the two years being compared; and (iii) the primary marker, the course instructor, remained constant over the two years, ensuring a higher degree of reliability.

The scoring of the project, including both the written and the in class presentation, was (as described above) based on two broad NSF criteria: (i) What is the intellectual merit of the proposed activity?; and (ii) What are the broader impacts of the proposed activity? These were further elaborated by the instructor (see Appendix B) to ensure the scoring addressed the diverse course learning objectives (across the four categories).

B. Experience

Two approaches to measuring student experience were conducted in this study, the first quantitative and the second qualitative. In the first, the students were asked to complete the standard university course and teacher evaluation survey which asks the students to evaluate their experience of the course with respect to five items on a scale of 1 (low) to 6 (high). This instrument provides a measure of the student's general experience of the course, including the instruction, the intellectual challenge, and their perception of their own learning gain (see below). It is worth raising concerns that such student ratings may be biased by the marks or grades they receive. Research, however, has found that students do not automatically give higher ratings to classes in which they receive the highest grades [17]. In addition, in this study the university evaluation forms were completed before the grades were available.

In the second method, the students' experience of the course and teaching strategy was evaluated by a nominal group process [10]—in this case a Small Group Analysis (SGA) independently conducted near the end of the 2002 course by a trained evaluator from the Searle Center for Teaching Excellence. During an SGA, the

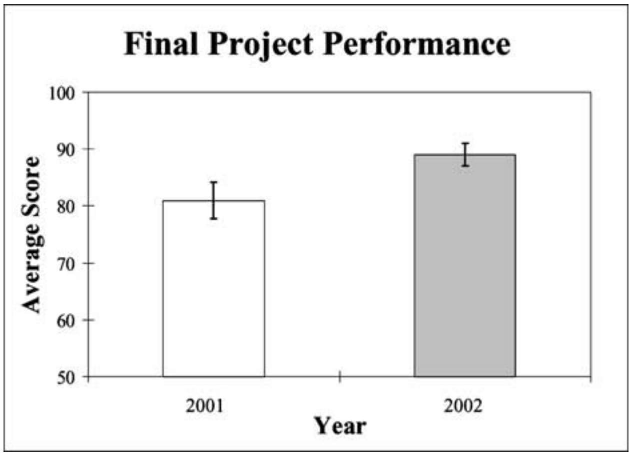

Figure 1. Results from the students' project marks for Nanomaterials taught in Spring 2001 ($n = 17$) and Spring 2002 ($n = 16$). $p < 0.001$. Error bars indicate standard error [19].

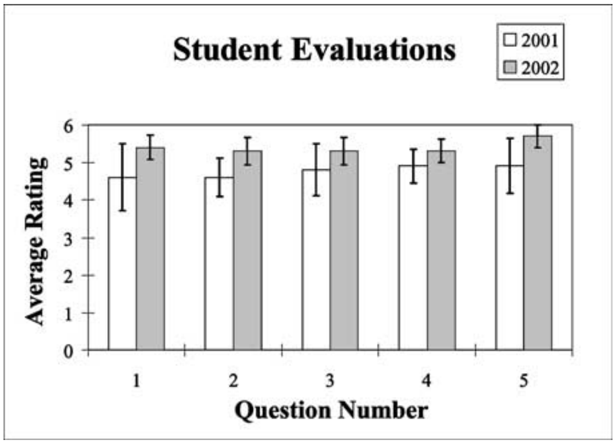

Figure 2. Results from student evaluations for Nanomaterials taught in Spring 2001 ($n = 10$) and Spring 2002 ($n = 15$). The students rate five aspects of the course on a scale of 1 (low) to 6 (high). Question 1 = Provide an overall rating of the instruction. Question 2 = Provide an overall rating of the course. Question 3 = Estimate how much you learned in the course. Question 4 = Rate the effectiveness of the course in challenging you intellectually. Question 5 = Rate the effectiveness of the instructor in stimulating your interest in the subject. Error bars indicate standard error [19].

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[1] Ideally we would conduct a randomized, controlled experiment and employ pre and post tests to measure a number of the course learning outcomes. Given the constraints of the educational situation, however, this was not possible. In further evaluations of the course, we would hope to address such limitations.

Student Consensus	Illustrative Comments
Collaborative projects improved learning, particularly deeper conceptual learning.	"Group activities tend to increase our learning over traditional homework sets." "We can always look up formulas, but we don't always get the theoretical or conceptual basis behind it."
Interdisciplinary exposure extended knowledge base and improved learning.	"Through group work we have been exposed to different disciplines and backgrounds. This has really helped us learn." "(The course encouraged) interactive learning between people of different majors, backgrounds." "Real world assignments are useful."
Problem-based assignments contributed to relevance of course and intrinsic interest in further personal learning.	"I have been exposed to things that I never even knew were possible or existed. The wide exposure to so many concepts is highly beneficial, and opens the road for further personal investigation."
Peer projects and assessment improve interpersonal and social skills.	"This is the first class in which I have had to work in groups. I have learned a lot about working with my peers and doing group presentations. I think these are valuable skills."

Table 3. Impact of pedagogical practices on student learning.

instructor leaves the class and the evaluator splits the students up into small groups of three or four. The groups are asked to consider a number of written questions about the strengths/weaknesses of the course and the instruction with respect to their learning. Each group then writes down a collective response to each question. The collective responses are then shared with the whole class to clarify meaning and to come to a class consensus. By working in groups, a consensus opinion is formed rather than a potentially unrepresentative sampling of the most adamant or vocal responses elicited from a large group. The purpose of the SGA was not for comparison between groups but rather to learn more about how students in the redesigned course experienced the teaching practices in terms of the four categories of learning outcomes described earlier.

V. FINDINGS AND DISCUSSION

A. Performance

A major source of concern for faculty introducing pedagogical practices such as those described in this paper is the fear that students will not learn the material in the syllabus and that the pedagogical process will undermine the product—the students' knowledge. The findings from the comparison of the project scores between the two years included in this study (Figure 1) indicate that this is not the case. Indeed, the students' performance across a diverse set of learning outcomes appears to be substantially enhanced by the pedagogical practices introduced[2]. The mean student projects scores improved from 81.2 percent in 2001 to 89.1 percent in 2002, almost a full grade. Despite the modest number of students being compared ($n = 16$ and $n = 17$ respectively), this gain was statistically highly significant ($p < 0.001$). In addition, the effect size that may be attributed to the changes is 1.44, which is considerable given that effect sizes of 0.8 and above are regarded in the literature as high [18].

B. Experience

In both the 2001 and 2002 courses, the students appeared to be satisfied with the course and the pedagogical approach employed (Figure 2). Despite the relatively high scores for the 2001 course, the scores for the 2002 course were appreciably higher. All five survey items received higher ratings in 2002. The mean score changed from 4.8 in 2001 to 5.4 in 2002. Despite the modest number of student responses ($n = 10$ and $n= 15$, respectively), the gain was statistically significant for question 2 ($p = 0.029$) and question 5 ($p = 0.030$) and the effect sizes for all questions ranged from moderate to large (0.56–0.93). The highest-ranking topic (receiving a mean score of 5.7 in 2002) was the effectiveness of the instructor in stimulating interest in the subject. Besides challenging students intellectually, the pedagogical practices employed in this course appear suitable for generating enthusiasm about nanotechnology.

The findings from the small group analysis conducted with the students in the 2002 course were similarly positive. Although the unorthodox teaching style and peer assessment methods were expected to lead to some anxiety among the students, the students uniformly expressed enthusiasm for the assigned group activities and the four pedagogical practices embedded in this strategy. Key qualitative findings with respect to these practices and representative comments from this evaluation are provided in Table 3. They

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[2] There were no appreciable differences between undergraduate and graduates performance or experience data in either of the study years.

indicate that the collective impact of the practices was academically constructive and effective with respect to the students' perception of their learning across the intellectual, practical, social, and personal dimensions of learning outcomes.

VI. CONCLUSIONS

The emerging field of nanotechnology presents unique pedagogical challenges due to its interdisciplinary and nascent character. Consequently, a senior undergraduate and junior graduate level course was developed to provide the students with a much more realistic experience of working with nanotechnology by emphasizing interdisciplinary communication and higher level thinking outcomes including critical evaluation. The course design was primarily centered on group activities that used a combination of four nontraditional pedagogical practices: collaborative, interdisciplinary and problem-based group work in which students engaged in substantial and meaningful peer assessment. In the latter case, peer assessment was part of the overall summative course assessment, comprising 46 percent of the final grade. These practices effectively addressed and achieved the range of overall course goals, including practical, social, personal, and intellectual learning objectives as evidenced by improved student performance and experience according to both quantitative and qualitative measures. Since the educational issues surrounding nanotechnology are analogous to other quickly developing fields, it is likely that the approaches delineated in this paper can be applied to many different courses at the forefront of engineering.

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APPENDIX A

Nanomaterials Course Resources

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Note: The course notes also referred to a long list of journal articles. These articles are referenced on the course web page which can be found at the following internet address: http://www.hersam-group.northwestern.edu/.

APPENDIX B

Nanomaterials Final Project Evaluation

Grading: Written report grade from instructor: 50%, Presentation grade from instructor: 30%, Presentation grade from classmates: 20%. The evaluation criteria for the presentations and written report will be the same that is used by NSF:

1.) **What is the intellectual merit of the proposed activity?**
    - To what extent has pre-existing literature been surveyed and critically evaluated?
    - To what extent does the proposal creatively advance the state-of-the-art?
    - How realistic are the proposed processing strategies for controlling nanostructure?
    - How effective are the proposed nanostructures in achieving the desired properties?
    - How well conceived and organized is the proposed activity?
2.) **What are the broader impacts of the proposed activity?**
    - What applications will be possible if the proposed activity is successful?
    - To what extent will the proposed activity impact the environment, national security, energy, society, and/or the economy?
    - To what extent does the proposed activity utilize or promote interdisciplinary collaboration?
    - How effectively will the results of the proposed activity be communicated both within and beyond the scientific community?

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