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A Nanotechnology Course for Undergraduates*

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A new sophomore-level nanotechnology course was developed and co-taught from seven disciplines: biology, chemistry, physics, materials science, electrical, mechanical engineering and ethics. The goal of the course was to provide a descriptive view of nanotechnology for biological applications. Several faculty members co-taught the course, and a course coordinator assisted in integrating the course content. Our new course was taught both in the spring 2004 and spring 2005. Our experiences learned from the 2004 course were transferred to the 2005 course. Our classes consisted of biology and engineering students. Because the backgrounds of the biology and engineering students were entirely different, the students were grouped into interdisciplinary teams on their class project and homework assignments. Teambuilding fostered better communication and improved learning.

Keywords: nanotechnology; teaching strategies; co-teaching

INTRODUCTION

MANY UNIVERSITIES teach courses in nanotechnology at the senior/graduate-level. However, few universities offer sophomore-level courses in nanotechnology. Possibly, this is because lower division students do not have sufficient knowledge in the basic sciences. The National Science Foundation (NSF) is interested in introducing nanotechnology at lower academic levels to produce students who are scientifically literate in this rapidly changing field and to encourage them to consider careers in nanotechnology [1]. By 2015, nanotechnology has been predicted to require 2 million workers and contribute US$1 trillion per year to the global economy [1]. According to the NSF, 'nanotechnology will not only be the fastest growing industry in history but also will be larger than the combined telecommunications and information technology industries at the beginning of the technology boom in 1998' [1].

Nanotechnology is a broad discipline requiring the integration of several science and engineering disciplines. Previous investigators have proposed an integration of the basic sciences in nanotechnology courses [2]. To our knowledge, most of these courses have been upper-division (junior/senior) and graduate courses for more advanced students. For example, at Northwestern University a junior-level course has been developed which is entitled, *Nanomaterials* [3]. Within the last few years, some lower-division nanotechnology courses have emerged in the US. [4]. More recently Rice University has offered a new lower-division course [5].

In 2004–2005, Loyola Marymount University (LMU) was awarded an NSF grant to develop and teach a new sophomore-level course entitled, *Introduction to Nanotechnology* [6]. Our course integrated a broad range of topics in basic science, engineering and ethics. Such diverse disciplines as biology, chemistry, physics, materials science, electrical/mechanical engineering and ethical/social values were taught at the sophomore-level. The purpose of our course was to utilize the basic and applied sciences for understanding the impact of nanotechnology on the human body and society. Our course satisfied the new educational trends of integrating the life sciences and nanotechnology into the engineering curriculum, as recommended by the American Society of Mechanical Engineers (ASME) [7, 8].

Our course has been taught every year from 2004 to the present. In this paper, we shall only refer to our course offerings in 2004 and 2005. The classes were organized according to a common goal, learning objectives, central theme, course outputs and outcomes. The course was open to both science and engineering majors, and it was co-taught by faculty members from several disciplines. In both course offerings, we had a coordinator, who assisted in organizing the course content over a 15-week semester. The instructors collaborated with each other every few weeks to coordinate the course architecture and topics.

COURSE ORGANIZATION

Goal and learning objectives

Our Course Goal and Learning Objectives have been combined with a logic model for assessment (Inputs, Activities, Outcomes and Outputs), which

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has been promoted by the NSF for project evaluation [9]. Figure 1 shows our logic model, where the Short-Term Outcomes and Inputs are linked to Activities. The definitions of these terms and examples of the logic model have been presented in a previous NSF workshop [10]. The logic model addressed our Short-Term Outcomes for formative assessment and our Outputs for summative assessment, which will be discussed in Section V.

In the 2004 course, 70% of our students were declared biology majors. The number of biology students increased to 85% in our 2005 course. The balance of students in our two courses were engineering students. Since the biology students had a limited background in mathematics and physics, our course had to be taught at a conceptual level. Our Learning Objectives were having our students understand the bio-nanotechnology applications, comprehending everyday literature (e.g., newspapers, magazines and trade journals), analysing the current ethical and social issues and understanding the design and fabrication of biosensors.

Course architecture

The preliminary planning of our new 2004 course has been previously described [11]. Since that time, we have made modifications to its content; the current version is shown in Fig. 2. Our course was divided into nine teaching modules. It started with an introduction (module 1, Fig. 2) that provided an overview of the seven disciplines (biology, chemistry, physics, materials science, electrical engineering, mechanical engineering and ethics) and their applications. The introduction presented a 'systems' approach to nanotechnology, where the individual disciplines were merged. This systems approach to problem solving has become popular in higher education. For example, 'systems biology' is being pursued at MIT [12], Harvard [13] and other US universities [14].

A systems approach to nanotechnology enabled the students to obtain a global perspective—an integrated 'view from the top.' The students were also exposed to size scaling (from large to small), e.g., height of a person (~1.7 m), size of a fly (2 mm), diameter of a human hair (~100 μm), cell size (~10 μm), virus size (~50 nm), and DNA width (~2 nm). The different size features were illustrated on a chart with a logarithmic scale covering the three size regimes: macroscopic (~1 m—10^{-3} m), microscopic (~10^{-6} m) and nanoscopic (~10^{-9} m).

The course was organized into nine modules (Fig. 2) and three biological applications: DNA microarrays, microfluidic (lab-on-a-chip) devices and bio-nanostructures. Moving 'top-down' in Fig. 2, the modules were divided into the science disciplines (modules 2–4)—biology, chemistry and physics. These disciplines provided the basic understanding of evolution, genetics, mutation, molecular/cellular biology, quantum physics, molecular chemistry and current biostructures. Two general types of biostructures were covered—natural molecules produced by the human body (e.g., DNA, RNA and proteins), and synthetic molecules or nanostructures (e.g. quantum dots, buckyballs and nanotubes). Because the nanostructures were <50 nm in size, they could penetrate cells and interact with the body's natural molecules.

Materials science (module 5) was the integrator of the science disciplines throughout our 2004 course. This is logical since materials science, like nanotechnology, is an interdisciplinary field. The surface-to-volume ratio of nanostructures was compared to the surface area/ volume weight of different cells, organs and organisms. The link between biology, physics and chemistry was

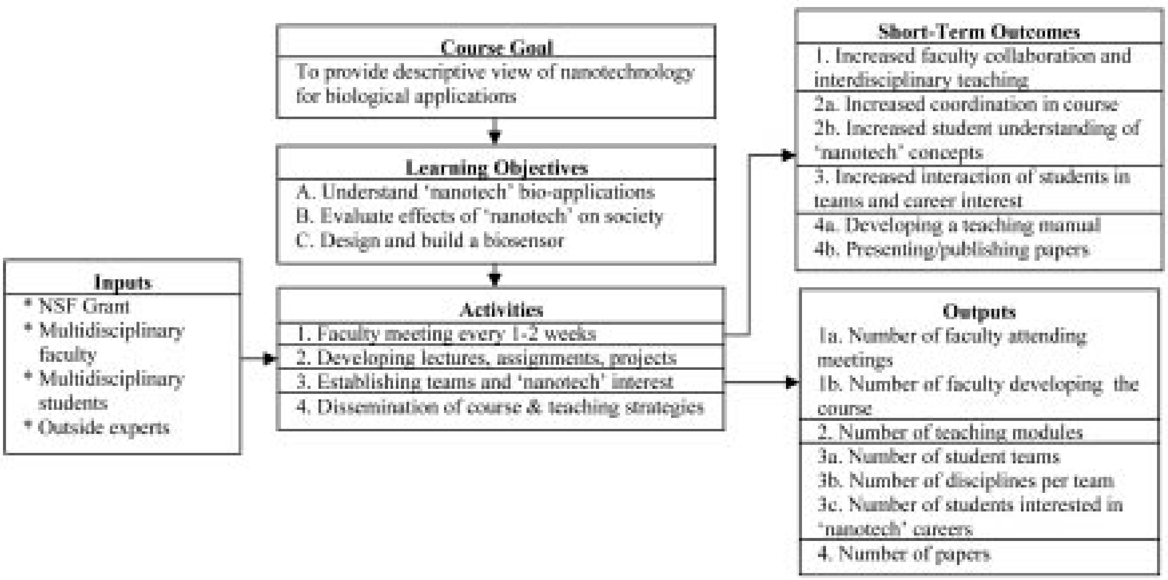

Fig. 1. Assessment logic model showing our inputs, goal, learning objectives, short-term outcomes and outputs.

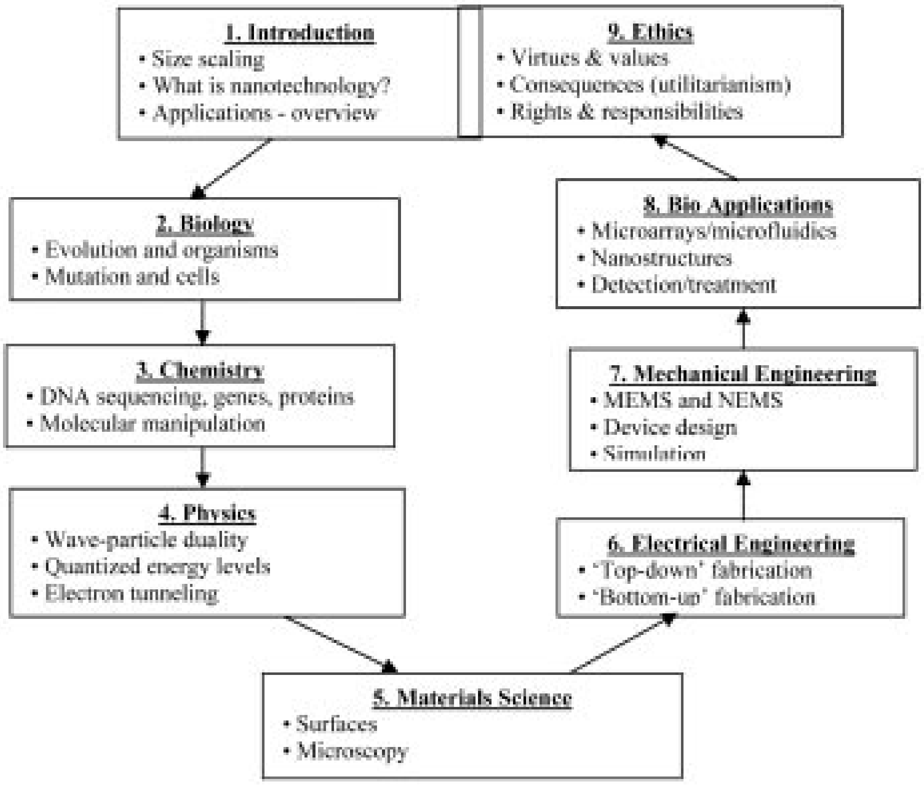

Fig. 2. Course architecture (modules 1–9) and flow of topics.

computer technology. Computers have enabled large amounts of genetic data to be analysed quickly. Hence, logic gates in computers were explained. This led into a description of field-effect transistors (as switches) and various electrical materials (i.e. conductors, insulators and semiconductors). The different types of microscopes for resolving the size scales were discussed (optical and fluorescent microscopes, scanning and transmission electron microscopes, atomic force microscope and scanning tunnelling microscope).

Moving 'bottom-up' in Fig. 2, materials science was transitioned into applied systems (modules 6–9)—electrical and mechanical engineering, biological applications and ethics. Electrical and mechanical engineering used the basic sciences to explain how to design and fabricate synthetic micro/nanostructures for specific applications. Electrical engineering discussed the design, operation and fabrication of transistors for complementary metal oxide semiconductors (CMOS). Mechanical engineering discussed the design and fabrication of micro-electromechanical systems (MEMS).

Three types of micro/nano-devices were discussed as bio-applications (module 8):

(1) microarrays for DNA analysis;
(2) microfluidic devices for chemical/medical diagnostics;
(3) nanostructures for detection and treatment of cancer.

Then predictions were made on future applications of bio-nanotechnology in the year 2020. Ethics (module 9) was approached by identifying the potential benefits/dangers of nanotechnology. Using an ethics model: virtues and values, consequences (utilitarianism), rights and responsibilities (VCR) [15] and the engineering code of ethics [16], we discussed such issues as health/safety, environmental toxicity and personal privacy/surveillance.

The students worked in interdisciplinary teams on a class project that included simulating microfluidics flow in a channel using CoinventorWare software [17], designing a DNA sequencer [17], photolithographic etching the DNA sequencer on a silicon wafer, and analysing an ethics case study. From the feedback on our 2004 course, the students felt the level of mathematics, physics and chemistry was too advanced. Hence, our 2005 course covered more topics in molecular/cellular biology and bio-nanotechnology applications.

TEACHING STRATEGIES

In planning and developing the nanotechnology course, our teaching strategies focused on the following:

- Having a course coordinator;
- Using common themes;
- Discussing biological applications;

- Merging the disciplines;
- Having interdisciplinary student teams.

Having a course coordinator

The success of the course hinged on our ability to move from one discipline to another and to integrate the course content. A course coordinator assisted the instructors in these activities and motivated them to collaborate with each other. In addition, the coordinator organized the instructors' ideas and worked with them to design the course architecture and to develop their topics. In 2004, the faculty member in materials science acted as course coordinator. In 2005, the course coordinator was rotated to another faculty member. In the 2005 course, the coordinator modified the course based upon the experiences learned and assessment results from the 2004 course.

Using common themes

Common themes were established, and they were woven into the modules of the course. The themes were vital for inter-relating the seven disciplines (Fig. 2). Our primary theme was: 'the effect of nanotechnology on humans now and in the year 2020'. Size scaling was used as a secondary theme: 'relating the macroscopic world to the microscopic world to the nanoscopic world'. For example, the size scaling of blood vessels was related to the microscopic blood cell size and the nanoscopic DNA double helix size.

Discussing biological applications

During the early planning stage, it became obvious that the disciplines had to focus on the same biological applications. Any topic that could not relate to biological applications had to be removed from the course content. The three biological applications that we selected were: DNA microarrays, microfluidic devices and bio-nanostructures (e.g., buckyballs, nanotubes, 'caged' fullerenes, quantum dots, and nanoshells). 'Bio-nanostructures' were chosen because they could be used as bio-sensors for detecting diseases and as bio-actuators for treating the diseases. Each of the modules in Fig. 2 had to support at least one of our bio-applications. For example, if microfluidic devices were considered as the application, biology supported the diagnostic analysis; chemistry supported drug reactions; physics supported laser induced fluorescence; materials science supported the microscopy of micro-channels; mechanical engineering supported the design of micro-channels; electrical engineering supported the fabrication of micro-channels; ethics supported the benefits vs. dangers of nono-drugs. In 2004, an ethics faculty member participated in the course [18]. Also in 2004, the faculty members collaborated with industry, i.e. Nanostream [19] in chemical analysis, and NanoInk [20] in lithography. These industrial products were shared with our students.

Merging the disciplines

In a mini-plenary session at the 2003 Annual American Society for Engineering Education (ASEE) Conference, the deputy director of the NSF made the following statement: 'Nature doesn't have disciplinary boundaries' [21]. Often it is our educational system that creates the disciplinary boundaries. Since nanotechnology is very cross-disciplinary, the different disciplines need to be integrated. Figure 3 shows a Venn diagram that integrates the boundaries between engineering, physics, chemistry and biology disciplines. Nanotechnology is at the centre of the diagram, flanked by eight intersections of several cross-disciplines.

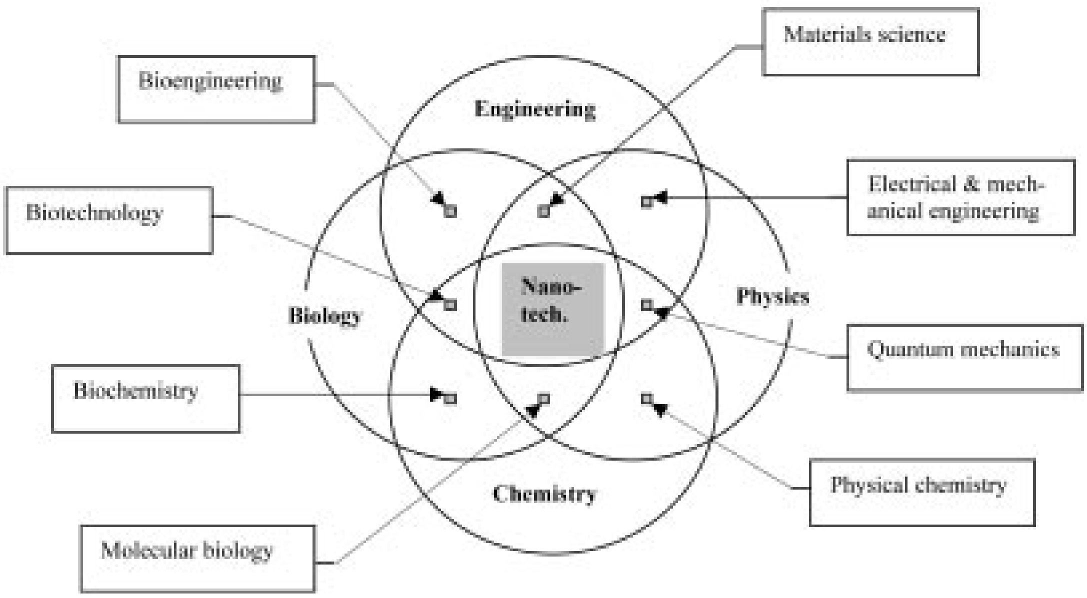

Fig. 3. Venn diagram showing the interdisciplinary nature of nanotechnology (called 'nanotech')

The invention of new nanotechnology products and processes has been predicted to occur at the intersection of the disciplines [1]. The purpose of our course was to merge the disciplines. Our course also exposed the students to the current 'nanotech' and 'biotech' definitions, even though a common language for 'bio-nanotechnology' has not been fully developed.

In the 2004 course, our intent was to reduce the gaps when moving from one discipline to another and to overlap the lecture topics. For example, overlapping biology and chemistry was obvious in discussing DNA, RNA and proteins. Other examples included combining:

(1) biology and physics in discussing the application of quantum dots for detecting cancer cells;
(2) chemistry and materials science in discussing nano-particle surfaces;
(3) physics and electrical engineering in discussing field-effect transistors in computers for analysing genetic data;
(4) biology and ethics in discussing genetic engineering and increasing the longevity of humans.

The first time the course was taught, the faculty members had great difficulty overlapping topics and reducing the gaps between one discipline and another. The lectures sounded more like 'tag-team' teaching than integrated teaching.

In 2005, having taught the course once before, the faculty members were more familiar with each other's discipline, and this made integrating the disciplines much easier. In addition, only three faculty members co-taught the 2005 course, which prompted them to better overlap their topics. Table 1 shows the three faculty members by discipline, who taught the 2005 course, and the course modules they taught. Hence, reducing the number of instructors forced the faculty to teach modules that were outside their discipline, which automatically promoted them to merge of their disciplines.

Interdisciplinary student teams

The students were grouped into diverse teams of 3–4 students per team according to the students' major, grade-point average, gender and ethnicity. For the most part, the students were sophomores, who declared their major to be either biology or engineering. In both 2004 and 2005, there were 29 students in our course from biology, electrical and mechanical engineering. In 2004, about 70% of these students were biology majors, and 48% of the class were women. In the 2005 course, about 85% of the students were biology majors, and 40% of the class were women. The teams were selected by the faculty to be both diverse (as discussed above) and balanced, where each team had at least one engineering student on it, with the remainder being biology students. Student diversity and balance in teams have been shown to be important factors for improving creativity and productivity [22].

Table 1. Faculty's discipline vs. 2005 course modules that were taught (from Fig. 2)

Faculty's Discipline	Modules (1–9) Taught
Mechanical Engineering	1. Introduction 7. Mechanical Engineering micro-electromech, systems 9. Ethics
Biology	2. Biology 3. Chemistry 8. Bio Applications
Electrical Engineering	4. Physics 5. Materials Science Device fabrication 6. Electrical Engineering

In addition, it was expected that the students would learn by collaborating with their teammates in small groups to reinforce the course fundamentals in both their class project and homework assignments. Collaboration in teams has been shown to enhance student learning [23]. Their class project was worth 40% of their grade, and it consisted of simulating DNA electrophoresis in a microfluidic device and designing/fabricating a DNA sequencer and analysing an ethics case study in bio-nanotechnology.

ASSESSMENT METHODS

Several methods were used to evaluate both our Short-Term Outcomes (formative assessment) and Outputs (summative assessment) [8]. Formative assessment provided internal feedback to the faculty members for making corrective actions to improve the course. Summative assessment demonstrated our 'value-added' to the sponsor [9] for funding our grant. Both of these assessment methods were valuable in evaluating our course and undergraduate curricula [24]. The following four assessment methods were used in the 2004 course. Only the first and third tools were used to assess the class of 2005, as discussed below:

(1) Pre-test/post-test;
(2) Fast feedback questionnaire;
(3) Post-mortem course evaluation;
(4) Brainstorming interview.

Pre-test/post-test

The pre-/post-test consisted of ten multiple choice questions that were taken from the most important topics of our course (covering all seven disciplines). The original ten questions are shown in the Appendix, p. XX. The pre-test was conducted at the beginning of the course, and the same test was administered at the end of the course (post-test). The difference between the two scores was an 'indicator' of the degree to which our students grasped the course concepts. These results will be discussed later.

Fast-feedback questionnaire

This tool was used once a week to determine the students' progress in learning the material. It provided an anonymous snapshot on how the class was doing [25]. In the 2004 course, this questionnaire gave the instructors instant feedback, which enabled them to make modifications to the course before the semester ended. The main questions in the questionnaire were: 'What are the most important things you learned this week?' 'What concepts are you having the most trouble learning?' 'What single change by the instructors will most improve your learning?'

We implemented the 2004 fast-feedback results into our 2005 class. However, this questionnaire was not used in the 2005 class, because the students' response in 2004 was the same week after week. The biology students kept saying they were having trouble with mathematics, physics and engineering, and the engineering students were having trouble with biology and organic chemistry. The faculty took corrective action in 2005 by making the course more conceptual in order to seek a happy medium between the two student populations.

Post-mortem course evaluation

At the end of the spring 2004 and 2005 semesters, our course was assessed by how well we accomplished our Learning Objectives and Short-term outcomes. Since this evaluation was administered at the end of the course, it was too late to improve the current course. Hence, we coined the term 'post-mortem' course evaluation. The results of the 2004 course evaluation were implemented in the 2005 course.

In this assessment tool, we evaluated Learning Objectives A, B, C and Short-Term Outcome 2b (Fig. 1) by using the following statements:

(1) The course exposed you to the applications of bio-nanotechnology.
(2) You learned how to analyse the bioethical implications of nanotechnology on society.
(3) You designed a bio-sensor in the class project.
(4) The course prepared you for comprehending articles in newspapers, magazines and trade journals.
(5) The course helped you converse in the inter-disciplinary language of bio-nanotechnology.
(6) The course utilized nano-science basics to explain the bio-applications. For each statement, the students were given five choices, and the statements were scored on a Likert scale: where 1 = strongly disagree, 2 = disagree, 3 = undecided, 4 = agree, and 5 = strongly agree.

Brainstorming interview

At the end of the 2004 course, the Dean of Science and Engineering conducted a brainstorming interview with our students when the faculty members were not present. The Dean asked two qualitative questions: 'What did you like about the course?' and 'What didn't you like about the course?' The Dean took notes, which were later shared with the faculty members. The brainstorming interview was not conducted in 2005, because major changes had already been made to our 2005 course. These changes will be discussed later

ASSESSMENT RESULTS

Pre-test/post-test

The results of the average scores on the pre-test and post-test are shown in Fig. 4. In the 2004 course, the average score for the post-test (53%) was more than twice that of the average pre-test score (23%). In the 2005 course, average score for post-test (69%) was three times higher than the average pre-test score in 2004. Hypothesis testing was conducted on these data, and it indicated these results were significant at a 95% level of confidence [26]. If the difference between the post-test and pre-test results is assumed to be an indicator of student learning, the students had a better understanding of nanotechnology concepts after our course than before our course.

Fast-feedback questionnaire

As previously mentioned, this tool was only used for the 2004 course. Week after week during the

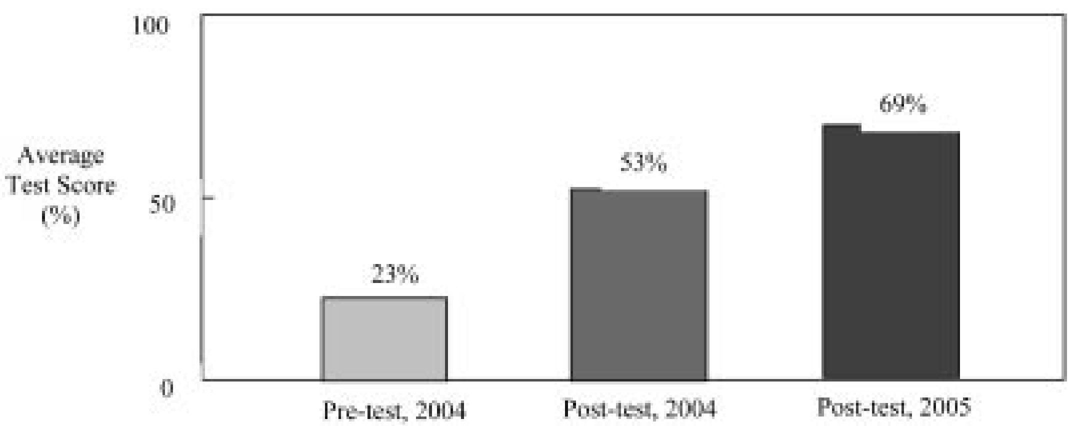

Fig. 4. Results of the average test score vs. pre-testing and post-testing in 2004 and 2005.

2004 course, the results of the questionnaires indicated a conflict between the biology students (~70% of the class) and the engineering students. The biology students felt comfortable with the biology, chemistry and bio-applications but felt very uncomfortable with the level of physics, mathematics and engineering. On the other hand, the engineering students had some difficulty with the biology and chemistry; and they wanted more physics, mathematics and engineering in the course.

In 2004, we had attempted to solve this conflict by grouping the students into interdisciplinary teams, so they could collaborate with their teammates on class projects and homework assignments. It was expected that the biology and engineering students would work together and help each other understand the course material. However, the fast-feedback questionnaires revealed the course content had to be modified for its level of sophistication in mathematics, physics and engineering to accommodate our biology students. Similar adjustments in level had to be made in organic chemistry and biology for the engineering students. In 2005, the instructors co-taught the course using demonstrations, pictures, drawings, diagrams and verbal descriptions of the concepts, and using few equations. An example of our conceptual approach is described in a recent textbook [27].

The level of our course content deserves further discussion. It was supposed to be a sophomore-level introduction to the terminology, concepts, applications and ethics of bio-nanotechnology, as described in our Goal and Learning Objectives (Fig. 1). The course also was supposed to enhance interdisciplinary communication between the engineering and biology students, which had never occurred before. In addition, our biology students had not yet started their physics courses nor had they finished their mathematics courses. Similarly our engineering students never had biology or organic chemistry. Hence, a more advanced coverage of nanotechnology will have to wait until another junior-/senior-level course is offered. Additional nanotechnology courses are currently being considered.

Post-mortem course evaluation

After the course had ended, a student survey was conducted to evaluate how well our Learning Objectives and Short-term Outcomes were accomplished. The students were asked to comment on six statements that were scored on a 1 to 5 Likert. The average values of the six statements are reported in Fig. 5 from our Learning Objectives A, B, C and Short-term Outcome 2b (see Fig. 1). For example, the statement 'converse in nanotech language' refers to the students being able to verbally communicate with other people using the current bio-nanotechnology terminology.

In 2004, our standard for improvement on each Objective/Outcome statement was set at an average score of 3.5. Any score <3.5 indicated that corrective actions were necessary. Likewise, an average score >3.5 indicated that course changes were optional, not mandatory. Except for the students learning the bio-nanotechnology applications (item 1, Fig. 5), the average score for each statement (items 2–6) was <3.5, which indicated that major changes were necessary.

For the 2005 course, we made changes in order to improve our teaching methods and/or course content. Our corrective actions were:

(1) to reduce the number of faculty teaching the course from eight to three;
(2) to reduce the amount of material covered, but to cover it in more detail;
(3) to reduce the level of mathematics, physics, chemistry and biology in the course and to provide a more conceptual approach to nanotechnology;
(4) to write more lecture notes on the chalk board, rather than using PowerPoint slides;
(5) to present the topics in a more organized way that better bridged the disciplines (Table 1).

Figure 6 shows the 2005 results of the same six statements that were used in the 2004 course (Fig. 5). In all cases, the average scores significantly

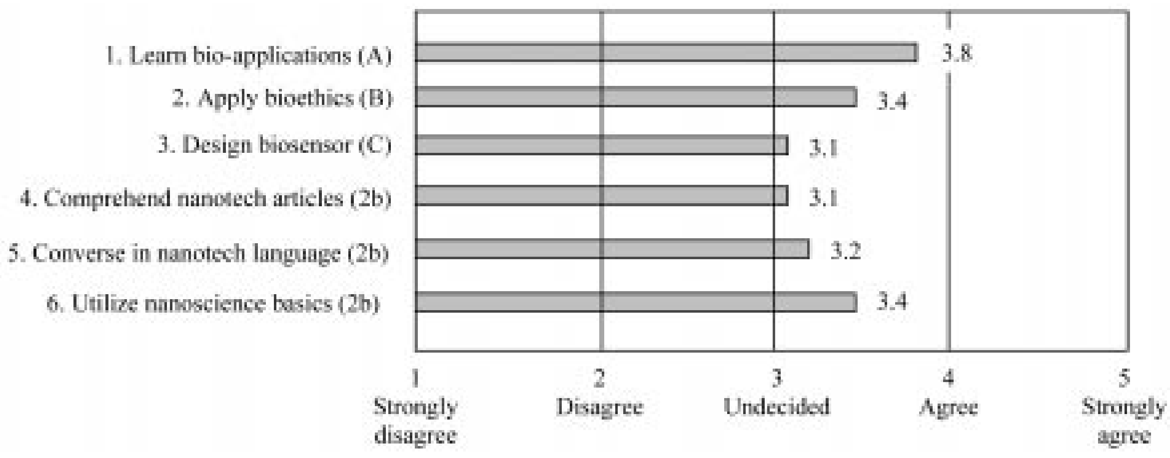

Fig. 5. 2004 Course average scores of learning objectives (A, B, C) and short-term outcome (2b) [see Fig. 1].

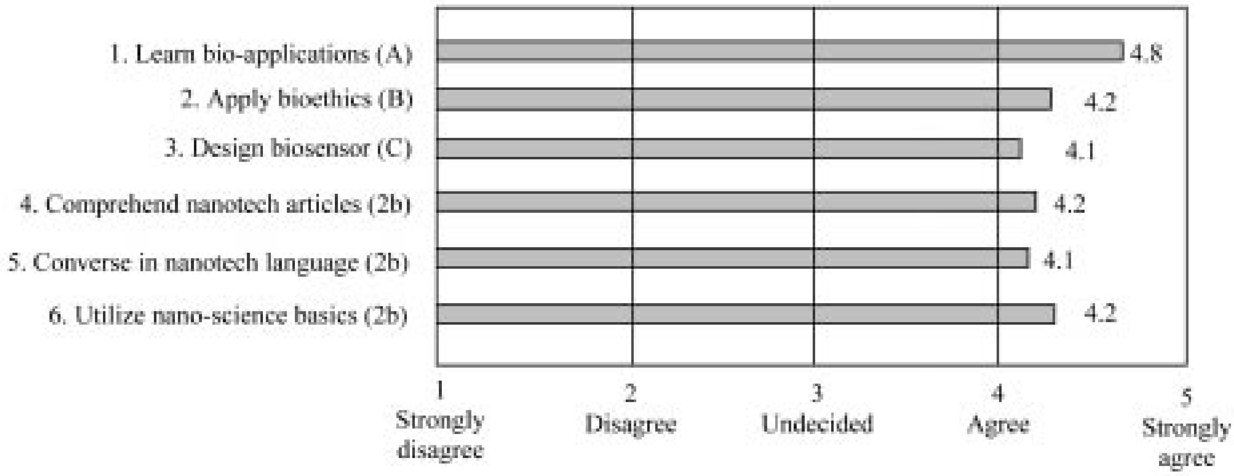

Fig. 6. 2005 course average scores of learning objectives (A, B, C) and outcome (2b) [from Fig. 1].

Table 2. Summary of results—brainstorming Interview in 2004 course

What students liked	Link to Outcomes & Outputs (Fig. 1)	What students didn't like	Link to Outcomes & Outputs (Fig. 1)
* Mixed teams (biology and engineering majors)	Outcome 3 Output 3a, 3b	* Too much material covered	Outcome 1, 2a Output 2
* Interesting topics	Outcome 2b Outcome 4a	* 8 faculty teaching course	Outcome 1, 2a, 2b Output 1a, 1b
* Hands-on team project	Outcome 3 Output 3a	* PowerPoint slides used for teaching	Outcome 4a Output 2
		* Physics, mathematics (biology majors). Chemistry, biology (engineering majors)	Outcome 2b Output 1b

increased over those in 2004; they exceeded our standard (3.5) for all six statements. This implied that our corrective actions yielded significant improvements in the 2005 course.

Brainstorming interview

A summary of the 2004 brainstorming interview is shown in Table 2. The table is divided into two parts: 'what the students liked' and 'what the students didn't like' about our course. Also included is the link to our logic model (Fig. 1) for numbered short-term outcomes and outputs.

In general, the students liked working in interdisciplinary teams, and they thought our selection of topics was very interesting. In addition, they liked doing project-based learning with their teammates. On the other hand, the students did not like the large amount of material that was covered in the course. They complained that the course did not have a textbook. We purposely did not use a textbook, because our faculty members felt the current books [28–31] would not be suitable for our introductory course. Therefore, the instructors compiled a teaching manual that consisted of their lecture notes, written text, PowerPoint slides, homework assignments, exams and team projects (Outcome 4a, Fig. 1). The contents of the teaching manual were given to our students throughout the semester. The teaching manual was assembled into the nine modules (Fig. 2). The faculty presented several papers at previous conferences [32–36] that described the general contents of our teaching manual.

In addition, the students did not like the number of faculty co-teaching the course, the way the material was presented using PowerPoint slides and the level of sophistication in the 2004 course (Table 2). Our corrective actions in response to these complaints have previously been discussed in our post-mortem course evaluation and fast-feedback questionnaire. Since the brainstorming interview elicited similar responses from our students as our other assessment methods, we felt it was excessive to continue the brainstorming interview in 2005.

LESSONS LEARNED

Our preliminary lessons learned are described from the perspective of our stakeholders:

- University infrastructure;
- Students and faculty.

University infrastructure

The curricula in science and engineering must change because nanotechnology is changing very fast. The intersection of nanotechnology and biotechnology will continue to drive this change. For example, biology students must have a better understanding of quantitative methods and mathematical modelling in order to solve problems in systems biology. Biology majors currently take physics in their junior year, but this occurs too late in their curriculum for our nanotechnology course. On the other hand, the engineering majors need more flexibility in their curricula. The engineering curricula are so tightly structured that the students do not have the freedom to take many electives outside their discipline. Hence, many engineering students are not able to take our course.

It is important that the Dean and department Chairs both support and reward faculty members for co-teaching our nanotechnology course. It is most important that each instructor who coteaches the course receives full-course credit (three semester hours). Our course requires that faculty members work together to coordinate their lectures. Teaching nanotechnology is not simply 'tag-team' teaching, because our faculty members must integrate their disciplines.

It is also important for the instructors to interrelate and bridge their disciplines to provide continuity. The nanotechnology topics can be overlapped from the top-down, which is called the 'systems approach' to education. In addition, faculty members need to be role models for the students in interdisciplinary learning, because future discoveries and inventions in nanotechnology will be made at the intersection of the disciplines. When the faculty members merge their disciplines, the students will be able to see how the disciplines work together to solve problems.

As previously mentioned, a teaching manual for our course was developed during 2004 and modified and upgraded in 2005. Unfortunately the teaching manual was not publicly available at that time. Based on our teaching manual, a textbook is currently being written that includes many examples, illustrations, problems and self-study questions [37]. In the meantime, several papers have been written that describe our course content [32–36]. This information was provided to our students. However, our students still missed not having a textbook to follow.

We suspected the students might have difficulty with our teaching manual, because it did not address the different learning styles of both student populations. For example, biology students had a tendency to learn by memorizing terminology and processes without using quantitative methods. On the other hand the engineering students learned by applying quantitative methods toward solving problems with little memorizing. Our teaching manual contained many PowerPoint slides in the 2004 course, which the students used as lecture notes. Since reading slides was considered passive learning, this was an ineffective way for the students to learn the concepts [23]. Hence, our teaching manual was revised for the 2005 course to provide more 'black board' discussions and group work for conceptual learning [27]. The teaching manual is being revised each time the course is taught.

Students and faculty

The challenge in teaching our course was dealing with two different student populations and their different educational backgrounds. The engineering students wanted more depth and quantitative methods and the biology students wanted more breadth and qualitative descriptions. Nevertheless, a common difficulty for all students was being able to scale nine orders of magnitude in size from macroscopic (~1 m—10^{-3} m) to microscopic (~10^{-6} m) to nanoscopic sizes (~10^{-9} m). Thus it is recommended that more size scaling examples and demonstrations be used throughout the course to better interrelate the different size regions.

The first year that the course was taught, our faculty members had difficulty integrating the course topics. In the second year, the instructors were more familiar with the bio-applications and were better able to overlap the course topics. Since the bio-applications of nanotechnology are so broad, it is recommended that faculty members focus their teaching on specific bio-applications. As previously mentioned, our applications focused on DNA microarrays, microfluidics and nanostructures. Ethics entered our course because the efficacy of nanotechnology is still unproven. The key question was: is nanotechnology beneficial or dangerous to our health? This question was addressed by applying the VCR ethics model [15] and the IEEE engineering code of ethics [16].

In the first year of the course, some faculty members had difficulty communicating with other faculty members. Because the instructors didn't fully understand each other's discipline, they were unable to speak the same language. This was probably symptomatic of our higher educational system, where a Ph.D. is acquired by understanding one's discipline in great depth, rather than having a breadth of understanding in science and engineering many disciplines. In teaching course, it was important for the faculty members to relate their discipline to bio-applications. In the 2004 course, the faculty members had a tendency to look within their own discipline rather than beyond it. The interdependency of the disciplines takes a long time to develop. This situation was certainly improved in the 2005 course. It is recommended that weekly seminars be conducted to help the faculty members think outside their discipline. This will enable the faculty to exchange knowledge and ideas, which can incubate joint research. Faculty members can also learn beyond their discipline by attending various short courses, workshops and tutorials [38–40].

Our faculty members had to relate to the bio-applications, but also to keep abreast of new developments in bio-nanotechnology in order to integrate them into the course. This is not a trivial matter for fast moving technologies. It is called 'lifelong learning' [24]. Hence, it was important for the nanotechnology faculty to continuously collaborate and share their knowledge with each other.

Many non-traditional educators are moving beyond the 'lecture/learn' format. There is strong evidence that students learn and retain knowledge better by 'doing' and by collaborating in groups, rather than by listening or reading [23]. Our faculty members have discussed the addition of a new teaching strategy—having a laboratory component in our course with experiments and projects. A combined lecture and laboratory approach for teaching nanotechnology has been successfully used at Beloit College [3]. This obviously requires more planning and coordination between the instructors. Teaching nanotechnology not only demands that the disciplines merge, but that instructors continually reinvent the course.

CONCLUSIONS

Our new sophomore-level course, *Introduction to Nanotechnology,* was developed and taught to biology and engineering students over a two year period. It integrated the basic sciences, engineering and ethics, and it provided a descriptive view on the impact of nanotechnology on the human body and society. Our course emphasized micro-arrays for DNA analysis, microfluidics for chemical analysis and medical diagnosis, nanostructures for detecting and treating diseases and ethics for evaluating the moral values of bio-nanotechnology.

The implications of our paper for teaching a lower division course in nanotechnology can be described as follows:

(1) Undergraduate curricula in engineering and biology need to be restructured. Engineering students should be exposed to biology earlier in their courses, and their curricula should have more flexibility for taking technical electives. Biology students should be exposed to college physics and mathematical methods before taking our course;

(2) Faculty members who co-teach nanotechnology should receive three units of credit toward their teaching load, because it takes extra time to coordinate course content and integrate topics. It is recommended that no more than three faculty members plus a course coordinator be involved in the teaching of this course. Instructors should focus on interrelating the disciplines and bridging the gaps between them. Faculty members should act as mentors for the students on interdisciplinary problem solving and learning;

(3) It is important to establish a course goal, learning objectives, a central theme and specific nanotechnology nano-applications. It is most beneficial to develop a structured course architecture. In addition, the outcomes, outputs and activities need to be identified for assessment purposes;

(4) A first course in nanotechnology should present a conceptual view of the subject, without introducing much mathematics, physics, chemistry and biology. The applications of nanotechnology and modern articles in newspapers, magazines and journals in the common, everyday literature should be emphasized in the course. More advanced nanotechnology concepts will require a second course to be taught at the junior/senior-level;

(5) As new discoveries and inventions are made in nanotechnology, instructors need to integrate them into the course. Changes in course content and teaching methods should be an ongoing process to keep improving the course;

(6) It is recommended that more size scaling examples and demonstrations be used throughout the course, so students can interrelate the sizes of different organisms, organs, tissues, cells and molecules over nine orders of magnitude;

(7) Forming diverse and balanced teams of engineering and biology students promoted interdisciplinary communication, which created a positive learning experience. Hands-on team projects allowed the students to merge their disciplines for solving problems.

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APPENDIX

Pre/Post-Test Questions

1. If you wanted to test the genetic history for both your Mom and Dad, where would the sources of DNA (for genetic testing) be located?
   a. Cell nucleus.
   b. Mitochondria.
   c. Y chromosome.
   d. All of the above.
   e. None of the above.

2. Of the following intramolecular forces, which is the most important in protein folding?
   a. Hydrogen bonding.
   b. Covalent bonding.
   c. Electrostatics.
   d. Hydrophobicity.
   e. Dipole-dipole attraction.

3. When fluorescence occurs in a quantum dot, what is the quantum dot emitting?
   a. Protons.
   b. Electrons.
   c. Neutrons.
   d. Photons.
   e. No emission occurs.

4. How many human hairs aligned together will fit into 1 mm?
   a. 1.
   b. 10.
   c. 100.
   d. 1,000.
   e. 10,000.

5. What causes the fullerene (C-60 buckyball) structure of carbon atoms to take the shape of a ball?
   a. Interatomic forces.
   b. Intermolecular forces.
   c. Capillary (surface tension) forces.
   d. Gravitational forces.
   e. Electron energy levels in carbon.

6. What is the advantage of anisotropic etching over wet chemical isotropic etching of silicon for a MEMS device fabrication?
   a. Anistropic etch rate is faster than isotropic etch rate.
   b. Anisotropic etching is cheaper than isotropic etching.
   c. Anisotropic etching provides better dimensional control.
   d. Isotropic etch rate is different in different crystal directions.
   e. Anisotropic etching provided sharper edge profiles.

7. What are the four ethical perspectives one can take to evaluate the issues in nanotechnology?
   a. Consequences, Rights, Values and Forfeitures.
   b. Justice, Virtues, Stakeholder Expectations and Relativism.
   c. Rights, Justice, Utility and Virtues.
   d. Rights, Consequences, Relativism and Utility.

8. Which of these statements is true?
   a. Cancer cells have lost control of cell division but contact inhibition and adhesion are normal.
   b. Cancer cells have lost contact inhibition and cell division control but adhesion is normal.
   c. Cancer cells have lost adhesion but show normal contact inhibition and adhesion.
   d. Cancer cells have lost cell division control, contact inhibition and adhesion.
   e. Cell division control, contact inhibition and adhesion are normal in cancer cell; other characteristics have been adversely affected.

9. Fluid flow in capillary electrophoresis is promoted by what?
   a. Application of surface forces from the conduit wall.
   b. Application of volumetric pumping forces.
   c. Application of electric fields.
   d. Application of laser energy.
   e. None of the above.

10. Which statement is true in comparing conductors with insulators?
   a. Conductors have more negative charges than insulators.
   b. Conductors have more positive charges than insulators.
   c. Conductors have a greater band gap than insulators.
   d. Conductors have more photons than insulators.
   e. None of the above.