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Pedagogical Challenges for Nanotechnology Education: Getting Science and Engineering Students to Examine Societal and Ethical Issues*

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There is a critical need for effective instructional methods that help future scientists and engineers participate in resolving societal and ethical issues brought about by innovation. This paper reports on the results of a multi-disciplinary, project-based instructional approach for college-level science and engineering students that integrated nanotechnology content-learning with the practical, social and ethical problems of nanotechnology application. Using a mixed method, pre- and post-instruction design the study examined students' perspectives and reasoning about the societal effects of nanotechnology discoveries. The results indicated that students had a cautiously optimistic attitude and that they maintained this position throughout the course. However, their reasoning for their attitudes noticeably changed after instruction. The detailed reasoning-analysis revealed students' deep-seated beliefs about the societal effects of nanotechnology discoveries. It also indicated the effectiveness of our instructional method to help students critically examine these prior beliefs and orientations. In specific, the findings indicate the need to consider quantitative and qualitative indicators of attitude about the social effects of scientific and engineering innovation in order to prepare students for the 21st century workforce. These findings guide our refinement of the instructional approach and can be informative for colleagues planning similar interventions in their curricular offerings.

Keywords: nanotechnology ethics; socio-scientific issues; multi-disciplinary education; student attitudes; reasoning about attitudes

1. Introduction

1.1 Motivation and objective

It is a prevailing perspective in the literature that a well-educated scientific and engineering workforce is pivotal for economic advancement [1, 2]. This manuscript argues that the rapid development in science and engineering fields, such as in nanotechnology, will require changes in our instructional approach to prepare the 21st century workforce. Nanotechnology involves manipulations of matter on the atomic and molecular scales that enable scientists and engineers to develop new technologies and materials. Innovations already made in this field include better treatments for diseases such as cancers, the development of cheap and transportable ways to purify water, and improvements in materials to efficiently use energy [2]. However, many of these processes have been associated with a certain amount of risk to human health and the environment [3, 4], and generated ethical concerns about human enhancement, the potential widening economic gap between nations, and privacy, among others [see 5, 6, 7 for an overview of risks and other ethical issues]. Coinciding with the presence of hundreds of nanotechnology based products on the market today [8], recent reports indicate that public interest in scientific advances is declining [9] and distrust in business leaders' ability to safely apply nanotechnology related scientific and engineering discoveries is prevalent [10]. Consequently, there is recent interest in educating scientists and engineers at all levels of expertise to consider the social and ethical implications of their work [11–13]. Traditionally science and engineering courses have not integrated the social-psychological factors of research conduct, therefore determining acceptable risks and applying appropriate ethical standards requires novel instructional methods. This study looks at the effectiveness of a project-based approach to teaching the societal and ethical impacts of nanotechnology discoveries in an introductory, interdisciplinary course.

Based on our own teaching in this area, our perspective is that discussing social controversies about the uses of novel scientific and engineering products is an effective way to raise the awareness of students about the societal relevance of their work. However, a related study [14] indicated that discussing the negative aspects of innovation in nanotechnology and other novel fields such as biotechnology

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can yield undesirable results such as increased focus on the risks rather than the benefits of innovation. In our course, targeting beginning scientists and engineers, such bias in instructional focus on risk could result in increased feelings of distance from the needs of society, or even direct opposition to consider the 'public good'. This would be in direct opposition to the improved motivation and knowledge we desire for these students so as to develop skills for innovation-fueled public advocacy.

A challenge for any instructional method in this context is that traditional education separates science and engineering students and further divides them into major fields (e.g. physics, biology, civil engineering, mechanical engineering, etc.). However, current discoveries are based on the combination of various disciplines. As a result, new fields, such as nanotechnology, emerge from sustained interdisciplinary work [2]. Similarly, science and engineering fields are segregated from humanistic and social science programs. This lack of communication among fields contributes to the perceived separation between ethics and scientific research that Berne reports based on her interviews with practicing nanotechnology experts [15]. Thus, it is a pressing pedagogical challenge to develop instructional approaches that help students engage with multiple disciplines as they formulate their professional identities and roles. Prior nanotechnology education efforts used science fiction to engage students in discussion of ethical issues [24], supplemented student-research with seminars on social issues [4, 25], and integrated ethics within interdisciplinary courses [26– 28]. Based on the above literature and our own experience, we identified the following challenge: How do we teach future scientists and engineers about the social relevance of their work without overemphasizing danger, risk and doom? Specifically, we want to encourage our students to reflect critically on societal and ethical issues, but encourage them to retain their enthusiasm for science and engineering. Our concerns in this area are based on the second author's experience integrating this content into a freshman introductory course targeted to high-achieving science and engineering students. She has observed that students can react to the introduction of risks and ethical concerns as being negative about the value of discovery. For some, particularly those most enthusiastic about technology, this approach conflicts with their expectations for a course focused on the positive benefits of technology.

Accordingly, this paper reports on the results of our instructional approach from a multi-disciplinary course for science and engineering students that combined instruction on nanotechnology content and ethical/social perspectives on nanotechnology applications to everyday problems. Specifically, this manuscript describes the (a) theoretical motivation for the study, the (b) instructional design choices associated with an integrated course, and (c) the results of the study on students' attitudes and reasoning about social-ethical issues brought about by nanotechnology discoveries.

1.2 Theoretical perspective

Some argue that ethical issues in nanotechnology are not unique, but result from 'convergence' among previously distinct technologies [e.g. 7]. In contrast, Berne [15] posits that nanotechnology requires specific ethical reflection. She argues that this is because nano-scale innovations are unseen and therefore inaccessible to the lay public. In addition, the degree of control promised by some of nanotechnology's proponents triggers cultural myths and excites human imagination to consider technological potential far beyond what is possible with current methodologies [pp. 77–78]. Thus, it is essential to examine social and ethical aspects in the context of nanotechnology-focused innovations. Like Hoover, et al. (27), we used Berne's (15) three dimensions to structure our approach to consider the ethical issues of scientific and engineering work.

Berne identified three dimensions to summarize the many issues related to examining the social, ethical aspects of nanotechnology discoveries: 1) practical issues around the responsible conduct and practice of scientific and engineering innovation; 2) normative issues involving societal perspectives on innovation to prevent problems arising from the new technologies; and 3) meta-ethical issues underlying deep seated beliefs about innovation and society [pp. 74–95]. She argues that training scientists and engineers on how to participate in discussions with the lay public on the significance of their work is a critical need for nanotechnology education—a sentiment also stated by Roco (2). However, Berne's interviews with currently active nanotechnology researchers found that they didn't feel qualified to comment on societal and ethical issues and/or that they saw ethics as a separate field from their technical specialties [p. 31].

Interestingly, educating for change in perception and behavior in light of social norms and personal values is a significant area of prior research in social-psychology. A particularly influential theory in this field that provided momentum for our work is the Theory of Planned Behavior (TBP) [16–19]. The TBP posits that attitudes towards a behavior are highly correlated with subjective norms (of society and friends) as well as personal feelings of control of one's actions. Prior studies on smoking cessation programs, starting and maintaining exercise programs and on-line shopping behavior illustrate these connections [20–23]. For our purposes, this theory provides three focal constructs that contribute to change towards responsible conduct of research (RCR) and public advocacy: (1) perceptions or attitudes towards a behavior, (2) social norms indicated by family and friends and (3) personal feelings of control for a particular behavior.

As the theoretical grounding for our study, we examined the similarities and complimentary aspects of the grounding theories above and arrived at our own theoretical framework by integrating these. Since this paper focuses on attitudes, we will connect the two theoretical frames using attitudes as a focus, though there are other possible connections between Berne's three dimensions and the constructs of behavioral intention as described by the TPB. As Table 1 documents, our research on students' attitudes was guided by elements of attitude about responsible conduct (dimension one), about normative issues that guide the social use of discovery (dimension two) and also touched upon examining students' attitude on meta-ethical issues.

With a focus on the critical need for research-based instruction in this area, we applied the above prior research and theories to examine students' perspectives and attitudes associated with their learning in a multidisciplinary course that integrated technical content with considerations of social-ethical issues related to discoveries.

1.3 Research questions

Supported by the above theoretical grounding the study set out to answer the following questions: (1) What do students think about social and ethical issues associated with nanotechnology? (2) What are students' reasons for their responses to issues of nanotechnology application? (3) How do students' views and reasons for these views respond to the instructional method? In the following we first provide the instructional context for our intervention then follow up with the research design, the empirical results and our discussion of findings.

2. Presentation

2.1 Methods

2.1.1 The instructional context

Our instruction was set in the context of coursework for an undergraduate Nanosystems Emphasis Area of study, funded by the National Science Foundation. 'Introduction to Nanotechnology Design' is a three-credit gateway course to the Nanosystems Emphasis Area and the instructional context of our research study. This course aims to help beginning science and engineering students, primarily freshmen, apply insights, methods and standards from the humanistic and social science disciplines to societal and ethical issues, in collaboration with researchers in different fields. This currently active, nine-credit Emphasis Area also includes three one-credit sophomore and junior seminars targeting research and proposal writing skills. The culmination is a three-credit senior capstone, wherein students move toward becoming independent researchers by working on interdisciplinary projects with mentor scientists and engineers.

Our overall objective for student learning

Table 1. Berne's three dimensions of nanotechnology ethics examined for implication for students' attitudes as a key construct of ethical conduct as behavioral intention (TPB)

DIMENSION ONE (practical issues): common assertions about the process of science (system, regulation, objectivity)	DIMENSION TWO (normative issues): dynamics of social processes related to research conduct (competition, dialog, peer review)	DIMENSION THREE (meta-ethical issues): deep seated personal beliefs about innovation in society (as related to purpose/nature of living, knowledge by humans)
Focal concepts for our work: students' values and reasoning for values related to practical issues of scientific discovery such as the processes of science, the responsible conduct of research and scientific objectivity	Focal concepts for our work: students' values and reasoning for values related the dialectic interactions between scientific discovery and societal progress due to discovery and technical advancement	Focal concepts for our work: students' values and reasoning for values related to their personal roles in innovation for improved knowledge and living condition on social scale
Guiding questions in our work: – What are issues of regulation and need for objectivity students know / need to know? – What are students' attitude responses to these practical, regulatory issues? – What values do students express about regulation and objectivity and how do these change via discourse and problem solving?	Guiding questions in our work: – What are issues of social interactions with peers (in this case nanotechnology researchers) and the public that students are aware of? – What are students' attitude responses to these societal issues of purpose and justice for humans? – What values do students express about the dialectic processes of conducting research in social context? How do these values change via discourse and problem solving?	Guiding questions in our work: – What are students' deep seated beliefs about the roles of scientists in social justice and economic progress? – How do students respond to the complexity of ethical action needed for social benefit? – What values do students express about their personal beliefs of purpose and how do these values change via discourse and problem solving? – How do students construct their personal, innovative roles in the contexts of societal discourse around technology?

responds to Berne's key finding that currently active nanotechnology researchers are reluctant to participate in public discussion of societal and ethical issues because they don't feel qualified in these areas and/or they perceive their technological research as separate from ethical reflection about its societal implications [15]. Therefore, our major objective was to give our students the awareness that scientists and engineers have significant contributions to make towards the public discussion of the implications of emergent technologies. Thus, we hoped to address what Berne identified as a critical need for nanotechnology ethics education. To achieve this goal, we had the following specific learning objectives for our students. By the end of the course, we wanted our students to be able to analyze and evaluate different positions on a variety of societal and ethical issues brought about by novel discoveries and to be able to construct ample reasoning for these positions. We also wanted students to appreciate the impacts of multiple disciplines, especially contributions from arts, humanities, social science toward reflection on societal and ethical issues (jointly referred to as 'socio-scientific issues', SSI [13]). Most importantly our objective was that by the end of course students will recognize that methods from the sciences and engineering alone can't resolve pressing social issues relevant to the use of innovations made by novel discoveries, but that scientists and engineers have a responsibility to contribute to public discussions and debate. Towards this end, we wanted students to develop nuanced views of societal and ethical impacts; recognizing that dialogue with the public can be as significant as specific solutions. Achieving this nuance requires that students can comfortably traverse between Berne's three dimensions [15] with the responsible conduct of their own research (Berne: dimension one), with the results of these research interpreted by considering normative issues involving societal perspectives on innovation (Berne: dimension two) and with personally reflecting on meta-ethical issues underlying deep seated beliefs about innovation and society (Berne: dimension three).

In our case, the specific content of the readings and exercises focused mainly on dimension two (normative issues involving societal perspectives on innovation). However, as we discussed these we also considered dimension three (meta-ethical issues underlying deep seated beliefs) specifically in terms of how meta-ethical issues frame normative issues. Similarly to Vanasupa, [26] and Hoover, et al. [27], we integrated practical, societal and ethical content with technical content in class activities and assignments, instead of teaching about practical, societal and ethical issues in separate seminars [4, 25] or modules [28].

To do so, students in this course did not simply receive content via instructor-lectures but they applied content knowledge to collaboratively and actively develop solutions to technical problems while determining the ethical and social implications of these solutions. Specifically, we aimed to use this strategy to train our students (future scientists and engineers) on how to approach societal and ethical issues so as to become more comfortable engaging in public discussions than the practicing scientists Berne interviewed. The preceding framework characterizes both problem-based and project-based pedagogical strategies which have been applied successfully in k-12 instructional settings [29] as well as in higher education, particularly medical education [30] and the training of engineers [25, 31–34]. Problem- and project-based pedagogies include the following core principles: an authentic problem to ground the learning experience that may be defined by the student or the instructor, solutions that are built from the students' own experiences, learning that is active and student centered and student-work that spans different disciplines as students apply knowledge in different contexts [31]. Although time intensive in nature and requiring substantial independent work by students, these strategies have been successfully applied at the freshman or introductory level [33]. Our specific strategy was project-based. Content was provided in a mixture of lecture, discussion and reading formats and additional hands-on skills were obtained in laboratories. Students applied this knowledge and skills in the context of a collaborative group project in which they developed an application of nanotechnology to meet a societal need. Groups identified solutions and related societal and ethical issues, conducted additional research, presented their work in oral and written formats, received feedback from instructors and peers, and used this feedback to revise their project. This cycle repeated three times and covered approximately two-thirds of the semester. Similarly to our own work, Sweeney, et al. [25] and Perrenet et al. [32] also used project-based learning in a nanotechnology context. They concluded that project based learning closely mirrored how engineers work in that it (a) required more definition and control by students over the topic of their projects as opposed to instructor proposed problems, (b) was supported by content delivered by more traditional formats, and (c) took a longer period of time to fully engage with the content, as opposed to traditional lectures.

Our course responded to the pedagogical challenge of developing an interdisciplinary instructional approach by applying a project based approach that combined content training in nanotechnology research and the examination of the social, ethical issues that this research brings about. To implement the instruction a team with multi-disciplinary expertise collaboratively designed and instructed the course. The team included mechanical and aerospace engineering, physics, biology, pharmacy, computer science and electrical engineering, chemistry, philosophy, and women's studies faculty, many of whom are nationally funded researchers with transformative interdisciplinary research programs [35].

The instruction covered topics such as the overall significance of nanotechnology, tools used in nanotechnology-research, significance of the nano-scale for the properties of matter (e.g. quantum mechanics, conduction), nano-materials, self-assembly, nano-based devices, and bio-macromolecules. Lectures, discussions, group work, laboratory assignments, readings and homework provided students with the technical and content background for the problem—and project-based learning assignments. Laboratory activities included using computers for modeling (MATLAB), microscopy, work with an atomic force microscopy, patterning, image analysis, and DNA extraction and analysis.

A variety of course readings related directly to Berne's second dimension by providing a broad overview of identified areas identified by Berne. The problem-solving and project-based activities on these issues were drawn from writings by scholars from a broad array of fields, including social scientists, natural scientists and engineers, humanists, and non-academics. Students used their learning in this inter-disciplinary setting to compose short essays on their positions on the various societal issues. These essays were used to assess their ability to solve a problem using the information and skills learned. The main project for the semester was a collaborative group assignment with the topic—within the context of nanotechnology ethics—defined by students. They were required illustrate how their project responds to a societal need and address practical and ethical issues. A significant portion of students' grade was on these ethical considerations. As part of instructional support students received extensive feedback from peers and instructors in the form of oral feedback, written guidance on projects and assessment rubrics. In the following we detail the motivation, methods and results of our research on how the instructional approached impacted students' views on the societal impact of nanotechnology discoveries, and the reasoning they provided for their views.

2.1.2 Research design

The study used a *mixed method* approach that was nested and concurrent by nature [36]. It was concurrent because it simultaneously collected qualitative and quantitative data and it was nested because it employed multiple instruments for the triangulation of data results. A *pre-post instruction design* assessed students' attitudes and reasoning before and after the instruction and the course activities described above. The *participants* were students at a large research university in a rural, Appalachian state in the US. The course is presented as an alternative to the second semester introduction to engineering course for students with an interest in nanotechnology. The prerequisite for this course (and the regular second semester introduction to engineering course) was that students had to have completed their first semester of calculus with a 'C' or better grade. Four of the fifteen participating students were female, half were freshmen, a fourth of the students were sophomores and a fourth were upperclassmen. Given that the course was a new offering, we allowed more advance students to enroll since they would not have had the opportunity earlier. One student majored in physics and the rest in engineering.

Data Sources included the pre- and post-instruction tests that employed brief statements about the application of nanotechnology in everyday settings, and asked students to indicate whether they agree with, disagree with or are neutral to each statement. The instrument used sample items from a previously developed survey [37] that was successful in prior studies on this topic (4). A question asking students to write a rationale for their agree/disagree choices was added in this study so as to document students' reasoning. An additional modification of the original instrument was the pairing of the negatively and positively formulated statements into issue themes. Due to the emphasis on positively stated questions in the original instrument [25, 4]; we selected only ten of the original 22 questions. These statements focused on five themes: Risk and Benefit; Sustainability; Abuse Potential; Economical and Environmental Effects; and Living Standards. For example: within the theme of 'Sustainability' the positive statement read 'Nanotechnology is a natural development of human evolution, so it will enhance survival' and the negative statement read ' Our most powerful 21st century technologies (i.e. robotics, genetic engineering and nanotechnology) are threatening to make humans an endangered species'. Accordingly, the adapted instruments used ten questions, five formulated with focus on the negative aspects of nanotechnology and five emphasizing the positives (Table 2).

The pre- and post-instruction responses were used to arrive at *two measures*: the value score, and the reasoning score. The *value score* indicated students' level of agreement or disagreement with a statement. For negative statements, agreement was

Table 2. The five societal issues examined by the ten statements on the pre- and post-instruction test with an illustration of the statements that probed each issue from a positive and a negative perspective

ISSUES	Orientation	STATEMENT of Test (Pre & Post)
Risk/Benefit	1+	Humans benefit from nanotechnology
	1–	Societal / ethical risks are not fully known yet
Sustainability and Survival	2+	Nanotechnology enhances survival
	2–	Nanotechnology devices make us less human
Abuse Potential	3+	The potential of abuse is overshadowed by benefit
	3–	Nanotechnology threatens people's civil liberties
Economy / Environment	4+	Nanotechnology enhances growth / environment
	4–	Nanotechnology creates environmental dangers
Living Standards	5+	Nanotechnology improves living standards
	5–	Nanotechnology widens the gap between nations

Score on positive statements	-2	-1	0	+1	+2
	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Score on negative statements	+2	+1	0	-1	-2

Fig. 1. Illustration of the method of arriving at value scores based on responses to statements formulated from positive and negative perspectives.

scored –2 (strongly agree), –1 agree). Agreement with positive statements was scored +2 (strongly agree), +1 (agree). Neutral responses received the score of 0 (Fig. 1). Accordingly, the mean value score associated with each question had a range of 4.0 (min = –2, max = +2) and the total score for all questions was maximum = 20 (range –20 to +20). With this method, we aimed to provide a normalized score calculation approach that allowed us to gauge perspectives in a balanced way. Fig. 1 illustrates this method.

The *reasoning score* was established based on students' written rationales for their agree/disagree choices. We examined these open-ended responses using methods for qualitative data analysis developed by prior studies [38, 39, and 40]. First, three coders repeatedly read each rationale. After reading and discussing the meaning of all rationales, emerging themes were identified by the three coders. Inter-rater reliability for coding was established using the following method: after individually scoring the rationales into the three themes, the three coders participated in a joint, inter-rater discussion session where all differences in coding were negotiated and a final coding choice was agreed upon. In this case the process resulted in 100% inter-rater agreement.

The *Data analysis* included two steps: the analysis of quantitative data (value score) was followed by the analysis of the quantified qualitative data (reasoning score). To answer the first research question the analysis determined the mean value score for all statements (all agree/disagree choices) as yielded by the pre-, and post-instruction tests. This analysis documented students' mean value scores before and after instruction. In order to answer the second research question, the qualitative data on the rationales for values were coded, tabulated into emergent themes based on the issues and perspectives they represented. These were then further condensed into the reasoning foci we report. Each rationale provided by students could refer to different themes, thus one response was possibly associated with several themes and reasoning foci. Accordingly, our analysis is focused on the themes of reasoning rather than individual students' responses. This analysis documented how students' reasoning for their opinions changed before and after instruction. To assess changes in value score after instruction, we tabulated the types of rationales (themes and focus areas) provided by the students, and visually examined the distribution of these before and after instruction. As part of the analysis to answer the second question we also compared the mean value scores on positively and negatively stated questions both before and after instruction. For this comparison we used a Wilcoxon Signed Rank Test for matched, related pairs. Developed to use for two related samples from a continuous field this test computes the differences between mean scores for each record and assigns a rank score based on this computation (see SPSS v. 18 [41] for details on the algorithm this test uses). Thus this test was ideal for use with our methodology and sample. To answer the third research question, we examined the pre-post instruction changes in students' value scores as well as their reasoning in the context of the specific characteristics of the student population we worked with. This summary allowed us to provide deeper detail about the context of our work and thus help readers interpret the relevance of our findings for their own work.

An important component of our research methodology was the division of labor and roles between the two authors of this manuscript. The second author was one of the instructors of the multi-disciplinary course and followed the students' work closely, including roles in classroom assessment for all contents. Thus she had deep understanding of the instructional context, as well as the characteristics of the students. She was able to bring that perspective to this manuscript. The first author collaborated with the second author on some of the assessments related to the ethics component of the course but never actually participated in the instruction. She worked with two student-coders to categorize code and analyze the data results. Whereas the data results, especially the coding choices for emerging themes, were shared with the second author for validation the quantitative and qualitative data summary was the primary responsibility of the first author.

2.2 *Results*

Overall, students maintained a cautiously optimistic attitude towards the societal effects of nanotechnology. A paired, two tailed t-test indicated that students' mean *value score* was in the low positive range both before and after instruction. A slight shift in mean score toward neutrality was observed after instruction, but this change was not statistically significant (Table 3). The overall shift in value score towards neutrality resulted from a considerable decrease in scores associated with positively stated questions and a slight move towards more positive value scores for negatively formulated questions. That is, responses moved toward the neutral on both positive and negative questions; however, this change was not statistically significant as illustrated in Table 3. Furthermore, when we compared the components of the mean value score for both pre-instruction and then post-instruction we found interesting results. A related sample Wilcoxon Signed Rank Test indicated that students' mean value scores on positively formulated statements was significantly different from their mean scores on negatively formulated statements. This statistically significant difference was observed both before instruction (Mpos = 4.60 SE = 0.67; Mneg = –1.07 SE = 0.56; p = 0.001) as well as after on instruction (Mpos = 2.27 SE = 0.84; Mneg = –0.87 SE = 0.70; p = 0.02). Given that we balanced positive and negative statements in our questionnaire (Table 2), this significant difference in students' value scores between positively and negatively formulated statements was not expected.

A more detailed examination of students' responses indicated that they agreed or strongly agreed with all positive statements; however, their responses on negative statements were more variable (Fig. 2). Students who had a highly positive perspective on an issue (indicated by strong agreement with a positively formulated statement) did not necessarily disagree with the paired negatively formulated statement. This agreement or strong agreement with positive questions was observed

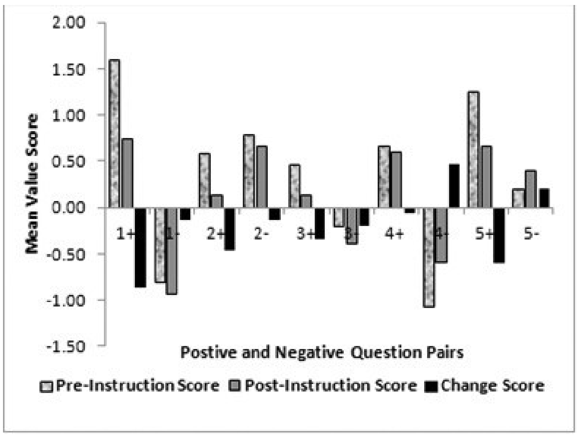

Fig. 2. Mean value scores on the pre- and post-tests, associated with each statement pair (a positively oriented statement paired with a negatively oriented statement in the same general area). The question pairs examined students' value scores in the areas of Risk/Benefit (1+ and 1–), Sustainability and Survival (2+ and 2–), Abuse Potential (3+ and 3-), Economy / Environment (4+ and 4–) and Living Standards (5+ and 5-). Value scores were calculated with a normalized method that considered statement orientation as shown in Fig. 1.

Table 3. Mean values cores before instruction (M = 3.53) and after instruction (M = 1.4) indicate a slight shift towards neutrality but this shift was not statistically significant (p > 0.18)

	PRE INSTRUCTION Mean Score (SE)	**POST INSTRUCTION Mean Score (SE)**	***df***	***p***
Mean Value Score (Max = 20)	3.53 (0.95)	1.4 (0.97)	14	0.21 (ns)
Value Score on Positive Statements	4.60 (0.67)	2.27 (0.84)	14	0.67 (ns)
Value score on Negative Statements	–1.06 (.56)	–0.87 (0.70)	14	0.78 (ns)

Note: p < 0.5 was used to determine significance of finding

Table 4. Example student statements categorized into themes within five focus areas: risk, benefit, practice of scientific discovery, lack of knowledge and ethical issues

FOCUS	THEME	EXAMPLE STUDENT STATEMENT
Risk Focus	Risk is prevalent in life Nanotechnology risk is possible	Every new technology has its risks, & it seems that w/ every new discovery brings an even bigger risk of us annihilating ourselves.
Benefit Focus	Benefits outweigh risk Potential benefit is high	. . . the good outweighs the harm . . . a great amount of benefit and can be widely applied.
Practice Focus	Cautious conduct needed Discovery is common practice	(Nanotechnology) can be a wonderful thing, but needs to be kept out of the wrong hands. We just need to be careful about some of the potential harm.
Lack of Knowledge	More research needed	More research must be done on its impact.
Ethical Issues	Social justice and shared benefit	I think nanotechnology will raise the playing field for survival between humans and nature as well as developed and developing nations. I feel that NT can have an immensely positive impact on society. However, as with any new technology the social and ethical implications must be taken into strong consideration.

both before-instruction (first bar for positive questions 1+; 2+, 3+, 4+ and 5+ in Fig. 2) and after-instruction (second bar for each positive question 1+; 2+, 3+, 4+ and 5+ in Fig. 2).

The analysis of *reasoning sores* focused on factors of risk and benefit that students associated with nanotechnology discoveries as well as the practical implementation of innovation while considering the lack of definite knowledge on scientific and ethical-, social-justice issues. Table 4 provides example reasoning statements students used, and illustrates how these were associated with different themes that emerged from the repeated reading of all statements in the five focus areas.

Our analysis found that the reasoning foci and emergent themes were used with different frequencies in students' reasoning before and after instruction. Before instruction, students' reasoning focused on the ubiquitous nature of discovery (as a common practice that is not different than what scientists have being doing for hundreds of years) and that innovation should be associated with norms such as cautious implementation and responsible conduct (32%). Pre-instruction reasons also focused on the benefit yielded by nanotechnology discoveries (29%), and noted the presence of risk (18%) as well as the need for more knowledge (24%) to make better decisions about nanotechnology impact. Only 9% of the reasons before instruction referred to the social or ethical issues brought about by nanotechnology discoveries (Fig. 3). After instruction there was a change in students reasoning patterns. Whereas they continued to focus on the ever-present nature of risk in the application of scientific innovation (25%); the potential benefits from these discoveries (25%) and the need for additional knowledge (17%), students' rationale after instruction used general, precautionary statements such as 'we just need to be careful' (8%) less frequently as compared to before instruction (Fig. 4.) Most importantly, after instruction,

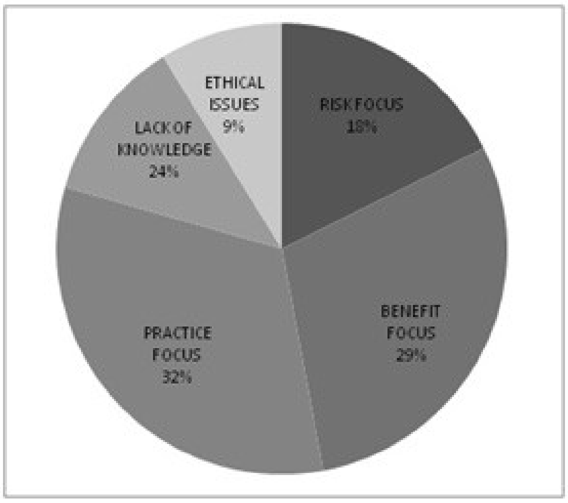

Fig. 3. The percentage of responses that fell into each of the focus areas before instruction.

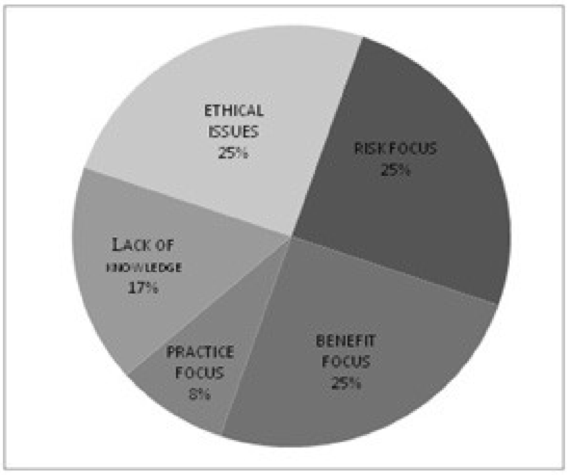

Fig. 4. The percentage of responses that fell into each of the focus areas after instruction.

students' reasoning included specific ethical issues that must be considered during the practical implementation of nanotechnology discoveries (25%). These included focus on social justice in benefit from discoveries, in economic consequences, and the responsible communication of risk and benefit. Table 4 provides examples on what the specific student statements were that fall into each of these categories.

3. Discussion

The instructional approach was intended to address the pedagogical challenge of integrating scientific invention with the social aspects of practical innovation. Although particularly relevant to emergent technologies, this approach has broader implications. Similar problems have been identified in teaching engineering students about design, given that students' immersion in science and technology coursework may lead them to downplay the impacts of disciplinary standing on how problems are conceptualized and neglect the role of social factors that influence how inventions are accepted and used [42]. Infusing perspectives from the humanities to engineering training has been identified as a possible solution to this issue [43].

This study examined the effectiveness of an innovative, multi-disciplinary course that used a project-based approach to integrate content learning and problem-solving practice. We were particularly interested in students' attitudes towards the societal effects of nanotechnology discoveries, since attitude, alongside social norm for an activity and perception of personal control for this activity/ behavior, are central factors in the development of behavioral intention [16–23].

Students thinking about ethical issues: Overall, students started the course with a cautiously optimistic view of the societal effects of innovation in the field of nanotechnology. This was evidenced by the mean value score that was in the low positive range before instruction. This value score decreased after instruction slightly (but not significantly). This decrease corresponds to prior findings by the Hart Research Institute [14] that demonstrated that even a short statement of potential negative outcome for nanotechnology applications served to significantly sway the general public towards more negative perspectives on these novel fields. In contrast to these prior findings however, in the current study the value score decrease was not a significant move towards negative values and opinions. This difference can be explained by both the characteristics of our science and engineering student participants as well as the success of our instructional approach for these participants.

Students' agreement with positive statements about nanotechnology is not surprising in a group of highly motivated engineering and science majors who selected the course based on a strong interest in the subject of nanotechnology. Both Bainbridge [37] and Sweeney [25] found that respondents who agreed with positive statements also disagreed with negative statements; although Sweeney [25] did note that the presence of some neutral responses. Therefore, the variation in our students' responses to negative questions puzzled us at first. Overall, they did not think that nanotechnology would threaten the existence of humankind or that one of the 'biggest risks' would be inequitable distribution of resources among nations with more or less access to the technology. In contrast, they did see potential risks arising from 'unknown environmental hazards' and some threats to privacy due to enhanced 'surveillance and information gathering'. Prior work by Berne [15] provides grounding to interpret this finding.

There is a dialectic relationship between risk and benefit as associated with innovation and the mean value scores indicate that students recognized this dialectic. While they continued to agree with the positive aspects of nanotechnology innovation they also saw the potential of risk, abuse, and negative consequences for the environment and society in general. The significant difference in value scores on positive and negative statements both before and after instruction indicates that students continued to aim to remain un-biased and justly consider all aspects of nanotechnology discoveries. We argue that this experience is necessary for novice scientists and engineers as it assists them in progressing on their developmental trajectory to become scientists who are able to and willing to communicate all aspects of their research with peers and the public. We feel that the multi-disciplinary instructional approach that integrated content learning with the examination of social and ethical issues effectively served this purpose. This success is illustrated by the finding that despite new knowledge on the variety of challenging issues associated with nanotechnology discoveries students were able to balance these negative perspectives with the benefits and advantages of nanotechnology discoveries. The analysis of students' reasoning for these opinions / choices, discussed in the next section, provided further evidence for the change in students' perception on the relationship of scientific discovery and the social and ethical aspects of the practical use of innovations.

Students Reasoning about Nanotechnology Application: The detailed analysis of students' reasoning revealed deep-seated beliefs that science and engineering students held about nanotechnology discoveries. It was not fully surprising that before instruction only nine percent of the reasons referred to the social or ethical issues of nanotechnology discoveries (Fig. 3). As discussed by prior studies [15], scientists and engineers are often not taught to consider the larger societal issues brought about by their research. However, students' in our study increased focus on ethical issues after instruction. This result indicates that the instructional method effectively supported students in developing important skills to change an outdated, traditional practice. Similarly to our work, Hoover et al. [27] also found that instruction on ethics in the context of an interdisciplinary approach promoted students' skills in critically examining their field. In fact, in the Hoover study, students cited the interdisciplinary nature of the course as a specific benefit. While our students maintained their cautious optimism after instruction, they were able to consider different perspectives (positive and negative) on the societal and ethical issues of nanotechnology research. These findings illustrate that we were able to present these controversies in a balanced way while drawing attention to controversial issues of social impact.

Considerations of instructional method: The results above clearly document that our instructional approach was effective to support students in their examination of the social, ethical implications of their work. However, the nature of our student population is important to consider in the interpretation of our results. These students applied to a special section of a required engineering course focusing on nanotechnology. They were aware that the course might include a heavier workload and more contact with research professors than regular sections. Thus, in addition to a pre-existing interest in nanotechnology, the students were also enthusiastically engaged with their intended majors. In some cases, this enthusiasm led to resistance for the detailed consideration of potential negative impacts of science and engineering. This supports the observation of the teaching professor (the second author) that students were in some sense threatened by the discussion of the potentially negative impacts of science and engineering. This is a key area to address with novel instructional methods because of the growing need for scientists and engineers to contribute to civic debate on scientific innovation and social progress.

Our findings mirror Berne's [15] conclusions from interviews with nanotechnology researchers. Her research identified specific 'conceptual blocks to ethics considerations' and indicated that her researchers' concern for ethical applications of technology were coupled with a 'feeling of powerlessness', particularly over decisions about how their work is used by society [15 p. 332]. Additionally, the scientists in Berne's study believed that their research and the ethics related to these discoveries were 'two distinct fields' [15 p. 332]. Sweeney's [25] finding that the attitudes of students' paralleled those of faculty and his conclusion that those findings showed that students were being enculturated into the norms of the profession further support our approach to develop research-based interventions for the training of young scientists and engineers. Based on our results, we argue that breaking down the separation between technical fields that produce innovation for social progress and academic disciplines concerned with the social and ethical issues brought about by these innovations remains a pivotal need. Thus, novel instructional methods that effectively respond to this need should be a regular component of university science and engineering education.

4. Conclusion

Our analysis of data from the pre and post-tests indicates that it is important to examine students' attitude with both quantitative and qualitative analyses methods. Look at student attitudes toward nanotechnology combined with the reasoning they give for their attitudes and values. Although attitudes may remain fairly constant and can indicate deep-seated beliefs if only examined with quantitative tools, the use of qualitative measures may provide opportunities for the deeper examination of factors of students' attitude. As our findings illustrate for example, students' reasoning can become more nuanced after they apply their knowledge by way of project based exercises on the social and ethical aspects of innovation and discovery. Based on our findings, we argue that training for young scientists and engineers may provide a means to develop a cadre of future researchers who understand how to maintain their professional roles while contributing to societal and ethical discussions and thus public literacy. If implemented on a wide-scale, such training will help us follow the recommendations of federal agencies that scientists and engineers reach out and participate in public debate on the social significance of their work. The research results on students' attitudes and reasoning for these attitudes support our argument, however additional work is necessary to refine this methodology for aspects of professional lives that go beyond the responsible communication of research. With description of our multi-disciplinary curricular approach and the results of our project-based instructional method, we aim to provide research-based information for colleagues who are developing innovative forms of instruction to teach young scientists and engineers about the social, ecological and human relevance of novel technologies. Further research is required to determine why students' may change their reasoning but not their attitudes and how this knowledge-development process is related to students' struggle to coordinate aspirations for innovation in science and engineering with the ubiquitous risk and danger that is associated with innovation in these fields. To this end, research that replicates the instructional method with higher number of participants and in a variety of instructional settings would be most beneficial. However, further refinement of the instructional approach may also be beneficial. To this end, we are in agreement with Berne [15] who argues that ethical and societal issues in nanotechnology cover a broad range of topics, some of which may operate in opposition to each other. For example, there may be broad benefits of certain types of nanotechnology whereas others may carry more risk. This has led to some concern that publication in research conducted in areas with more risk may disproportionately influence public perspectives in *everything* described as nanotechnology [5]. Whereas we included a wide array of issues from a balanced perspective in our measurement instruments, the more detailed examination of specific fields of discovery with different risk and benefit aspects may be needed for on-going instructional innovation.

Furthermore, professional behavior and effective public service in communicating research results in a balanced meaningful way does not stop at personal attitudes. Further research is needed in examining the relevance of additional factors of the Theory of Planned Behavior [16, 18, 22], such as social norms and personal feelings of control as well as economical constraints for implementing optimal behavior. A limitation of our study was that we were not able to follow the perspectives of individual students throughout our investigation. Consequently, we do not know how individual students responded to different types of questions in different contexts before and after instruction. Thus our continued work aims to provide additional, case-based examples of students' learning as related to their attitudes, norms and perceptions of behavioral control (components of ethical behavior as related to the TPB [16, 18]).

Motivated by these initial findings, the first author has been conducting research to further examine graduate students' development of attitude and reasoning about aspects of responsible conduct and communication of research (Berne's first dimension). The second author continues studies with undergraduate students to understand the development of students' meta-ethical thinking as they consider their scientific and engineering roles in the context of social responsibility (Berne's third dimension).

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