

Nanoscience in the Undergraduate Curriculum

Swarna Basu*

Department of Chemistry, Susquehanna University, 514 University Avenue, Selinsgrove, PA 17870

*Corresponding author: basu@susqu.edu

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Abstract The development and evolution of a special topics course in nanoscience for undergraduates is described here. Ideas for course design, assessments and activities are discussed, in addition to learning goals and how the goals were met and assessed. The goal of any special topics course should be to introduce students to up to date ideas and developments while including an overview of foundational concepts covered in previous courses. In addition, the right balance between content delivered through lectures and in-class discussions, and visualization through laboratory activities and experiments, is important. Finally, several aspects of course design and efforts to increase student interest and engagement are discussed.

Keywords: nanoscience, undergraduate program, course design

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1. Introduction

Contrary to widely held beliefs, nanoscience courses and research are not just the domain of large research institutions but are becoming more commonplace in predominantly undergraduate institutions (PUIs). There are several reasons for this. First, the novelty of the subject, even though research in the field dates to the 1980s. Second, the rapid developments and easy access to articles, videos and other sources of information make the course content very dynamic. And third, with the undergraduate research experience becoming an increasingly integral part of the education, many faculty are expanding their research interests to incorporate aspects of nanoscience as making nanoparticles isn't as cost prohibitive as one might imagine.

Of course, there are challenges as well. When it comes to embarking on new research projects, faculty at PUIs may not have access to the necessary characterization equipment like electron microscopes, X-ray diffractometers and particle size analyzers, and sending samples to nearby R1 institutions can be cost-prohibitive for those without large research budgets or external funding. Teaching loads and service courses may make it difficult for faculty to fit a special topics course into their teaching schedule. Finally, many institutions have a minimal enrollment requirement for their courses to be offered, and PUIs with small chemistry programs may struggle to attract enough students to make the course viable.

Articles about introducing core concepts of nanoscience at the college level (2006), designing courses for non-majors (2019) and introducing it at the high school level (2005) have been published in the past [1,2,3]. The goal of this commentary is to introduce fellow chemistry faculty to the development of a nanoscience course at a PUI and

offer ideas to not only make the content current and relevant, but also suggest ways to increase student enrollment and engagement.

2. Course Design and Learning Goals

Susquehanna University (SU) is a PUI located in rural, central Pennsylvania, with a total enrollment around 2200 students, where the total number of chemistry and biochemistry majors ranges between 50 and 70 across the four years. The ACS-certified department offers one special topics course each semester, and with seven full-time faculty, a course in Nanoscience would typically be offered every three years on average. Special topics courses usually require junior standing and completion of the introductory sequence (General Chemistry I and II, Organic Chemistry I and II) as pre-requisites. In order for the course to attract more students, it was approved to be an Interdisciplinary course in the Central Curriculum that also fulfills the requirement for the Biology and Biomedical Sciences majors, Biochemistry major, and as of 2021, the Chemistry minor. Enrollment data for the course is summarized in Table 1.

Table 1. Enrollment in CHEM 306 (Nanoscience). F = Fall, S = Spring. * First time the course counted towards the chemistry minor

Semester	F2006	F2008	S2013	F2015	S2019	F2021*
Total Enrollment	10	7	9	12	8	18
Non-majors	0	0	2	1	1	6

The learning goals for an interdisciplinary course at the time the course was last offered were as follows:

1. Explore and analyze the course topic(s) from the perspectives of at least two academic disciplines.

2. Demonstrate familiarity with the specialized vocabularies and fundamental concepts of said disciplines.
3. Show an appreciation of how different academic disciplines can supplement and reinforce one another.
4. Articulate an understanding of the complexities and ambiguities inherent in explaining issues from within the frameworks of at least two different academic disciplines.
5. Deliberately use the disciplines under study for analysis in a way that is not normally available to each discipline alone.

The course syllabus includes these learning goals and explanations of how the learning goals are to be met. A brief explanation is included below.

The course is designed around these five learning goals. The “perspective of at least two academic disciplines” is addressed through readings, discussions and laboratory activities that highlight the interdisciplinary connections between chemistry, physics, biology, and environmental science. The second learning goal is fulfilled using specialized vocabularies of chemistry, physics, and biology. For example, chemistry vocabulary is used to describe the synthesis and characterization of nanomaterials and reactions that occur in relevant processes; physics vocabulary is used to describe how nanoparticles interact with light and undergo energy changes; biology vocabulary is used to describe the applications of the nanomaterials to biological systems.

The course content and resources are chosen to ensure that students have all the necessary tools to achieve these learning goals. For example, the textbook takes an interdisciplinary approach and journal articles are selected to complement the topics being discussed in class. Both sources introduce students to the specialized vocabularies of different disciplines.

In recent years, there has been a lot of discussion around textbooks, especially with regards to cost and access. With more and more online resources and open-source content readily available, some instructors have moved away from requiring hardcopy texts, or even any texts at all. Also, nanoscience texts are often written for more advanced (graduate) levels and finding one that balances basic concepts with the big picture and is suitable for undergraduates can be challenging. A textbook is also a good source of review questions and homework problems. At SU, the current textbook is *Nanotechnology, published by CRC Press* [4]. Previously, *Nanotechnology: A Gentle Introduction to the Next Big Idea*, by Ratner and Ratner, was the primary textbook [5].

With the textbook providing a framework for delivering key concepts, the incorporation of literature articles, both recent and from the early-2000's, introduces students to latest developments in the fields as well as early conversations and discoveries. Without a look back in time, students would not be aware of the earliest findings, challenges, and conversations in the field of nanoscience, and they would not learn about interesting historical anecdotes like the ancient Egyptians dyeing their hair with lead sulfide nanoparticles or the use of nanoparticles in the Lycurgus Cup [6,7]. Journals such as *Scientific American* have featured articles by Paul Alivisatos (2007) and George Whitesides (2001), both pioneers in the field, and for recent findings, there is a vast selection of journals to choose from [8,9]. For a journalist's perspective on the

early days, Gary Stix's 2001 article titled “Little Big Science” is an excellent choice [10].

Literature articles are incorporated into the class in many different ways: 1. Students are assigned an article related to the current chapter and they are asked to read ahead, and the instructor simply incorporates content from the article into the lecture; 2. Students are asked to lead the discussion by presenting a figure; 3. Students are asked to provide discussion questions in advance and are called on to lead the in-class discussion; 4. Students are asked to give an oral or hybrid presentation on an article or nanomaterial of their choice. All of these are effective ways to get students to read and analyze journal articles, and popular choices have included articles on odd sources of graphene, effect of nanoparticle shapes, Vitamin C-conjugated nanoparticles, targeting cancer cells, toxicity of quantum dots, and DNA-based nanodevices [11,12,13,14,15,16].

To maintain student interest and increase engagement, the most current developments are introduced on a weekly basis in a segment called “Nano in the News”. There are websites that provide daily updates in the field, with most articles linked to a scientific journal and even videos. The incorporation of the latest findings, either through brief lectures or YouTube videos, helps break the monotony of a concept-heavy lecture and generates some excitement in the classroom [17,18].

Another way to introduce students to historical developments, and help make connections to the textbook chapters, is to incorporate a non-academic text like *Radical Abundance: How a Revolution in Nanotechnology will Change Civilization*, by K. Eric Dressler (PublicAffairs Books, 2013), who wrote the much-acclaimed book *Engines of Creation: The Coming Era of Nanotechnology* in 1986 (Anchor Books). Students are asked to provide discussion questions and lead the discussion of different chapters in class. These books offer not only a detailed look at the history of nanoscience, but also include plenty of examples and big picture connections that may be difficult to make with the content from a conventional textbook.

Teaching a course on nanoscience also provides an opportunity to discuss government funding, the grant-writing and peer-review processes, the responsibilities of various parties including the media and politicians, and the process by which information is disseminated. The roles of researchers and the average citizen are discussed in detail, and this makes for a very productive “Science and Society” segment and gives students a chance to engage on topics such as scientific literacy, research ethics, communication, bias, and pseudoscience.

The third and fourth learning goals are related to the first, and the fifth learning goal is met by integrating the knowledge from all three disciplines by combining the synthesis of nanomaterials (chemistry) with the characterization (physics and chemistry) with the applications (chemistry, environmental science, physics, and biology). The integrating of this knowledge is best illustrated through short lab activities that complement the in-class readings and discussion.

Given the “visual” nature of the content, such as color changes, applications, and characterization, a separate laboratory component would be appropriate, but that

would lead to scheduling issues as juniors and seniors are already taking one or two lab courses each semester. And when departments lack the necessary equipment to successfully implement several lab experiments, finding appropriate content becomes difficult.

When the course was first offered at SU, there was a separate lab section and most of the experiments involved the synthesis and UV-vis characterization of nanoparticles (ex. aggregation of gold nanoparticles, growth kinetics) [19,20]. Subsequent iterations of the course at SU have been in the form of a traditional lecture course that met two or three times a week. Twice-weekly meetings (Fall 2008) allowed for more time for lab activities, while thrice-weekly meetings (all remaining instances) limited class time to 65 minutes but several activities like surface-enhanced Raman scattering (SERS) and lithography were successfully implemented each time [21,22].

The importance of having a “visual” component beyond videos is important in any course, and at the minimum a nanoscience course should incorporate three or four short activities. Typically, the course at SU includes a lithography experiment and a solar cell experiment [22]. Items for the latter, and other potential experiments, can be obtained from the Institute for Chemical Education at the University of Wisconsin – Madison [23]. Additional experiments like building a prototype for microfluidics, “lab on a chip”, and synthesis and characterization of various nanoparticles have been done in the past [19,20], [24,25,26]. Most of these experiments can be completed in a single one-hour class if some advance preparations can be done, or the instructor can use one class for prep work (or synthesis) and one for the assembly and application (or characterization). Finally, these activities highlight the interdisciplinary nature of the course, and introduce students to the vocabulary and concepts from multiple disciplines, as required in the learning goals.

3. Nanoscience Content outside a Special Topics Course

Does a department necessarily have to offer nanoscience-related content only at the upper-level? The answer is no. At SU, experiments have been incorporated at the General Chemistry level. In years past, students have synthesized both gold and silver nanoparticles and studied the effects of salts and reaction stoichiometry on optical properties [20,24]. These experiments fit in nicely with lecture topics like the electromagnetic spectrum and colloids. SERS and zinc oxide nanoparticle growth kinetics experiments are also an integral part of Physical Chemistry courses [21,27].

“There are nanobots in the vaccine” – this was a common refrain that bounced around the internet and other sources when the Covid-19 vaccines were rolled out in late-2020. The use of lipid nanoparticles in the mRNA vaccines offered the department an opportunity to incorporate some nanoscience content in General Chemistry after a gap of several years [28,29]. The ferrofluids experiment has always been a popular one at all levels, and this time it was tied to not only nanotechnology, but also transition metal chemistry which fit nicely with the content being covered in the final weeks

of the course [30].

4. Student Perception and Engagement

“What do you know about nanoscience?” – this is a question posed to students on the first day of class. Until recently, most students claimed to know little about the field other than it being about really small things, but with references to nanotechnology in popular culture (Marvel movies) and the development of Covid-19 vaccines, students are more aware of the field [31]. When polled mid-semester about what they’ve learned the most about, students list applications, characterization, and types of nanomaterials among the top three. At the same time, when asked about what they would like to learn more about, a majority listed medical applications, environmental and health concerns, and nanomaterials already on the market, as topics they were most interested in.

When an upper-level special topics course is offered, the instructor must take many things into consideration. First, what is the most appropriate textbook, or is a textbook necessary? Second, what are the best ways to keep students engaged and interested in class? And third, what are the best forms of assessment for a special topics course with a very broad reach?

The choice of textbook and incorporation of additional readings have already been discussed. In terms of additional assignments, students benefit from regular homework assignments and short quizzes. While traditional exams are generally a useful form of assessment, in special topics courses, their use should be limited to one or two during the semester. Given the breadth of content and diverse array of topics covered, any exam should focus on basic concepts and theories that help students demonstrate understanding of the uniqueness of nanomaterials and their applications, and the physics, chemistry, and biology behind them.

While all the above forms of assessments and use of literature readings are common across a typical chemistry curriculum, other innovative approaches may be used to enhance student engagement. A discussion on the different topics is a nice way to set up a unique assignment – a mock Senate hearing. The idea of a mock congressional hearing in the classroom is not new and fits nicely into a “Science and Society” theme [32]. Smythe and Higgins described its use in an environmental chemistry course, and various simulations and role-playing exercises have been used at other institutions over the years [33]. At SU, this exercise was introduced in 2013 and has demonstrated to be very popular among students. The class is divided into three groups: 1. A group of bipartisan US Senators, each with their own expertise and agenda; 2. A group of researchers from different government agencies who are in favor of increased nanotechnology research funding; 3. A group of researchers from different government agencies who are opposed to an increase in nanotechnology funding, but not necessarily opposed to nanotechnology.

Prior to the hearing, each group of researchers submits a written summary of their arguments to the Senators. The summary contains all the key points the group plans to make at the hearing and the advance submission gives the

Senators time to prepare some questions. At the hearing itself, the researchers present their cases, individually, to the Senators, who then ask follow-up questions. After the Senators have heard from both sides, they are given an opportunity to ask additional questions. The researchers do not necessarily debate one another as the Senators are the ones facilitating any discussion. However, researchers are given the opportunity to counter any argument made by the other side. In the end, the Senators meet outside class and submit their “recommendation to the full Senate”. Students have commented that this experience facilitates learning in an “interactive, fun way”. In 2021, issues surrounding the Covid-19 pandemic were incorporated into the hearing with the inclusion of the director of the National Institute of Allergy and Infectious Diseases (NIAID) as one of the panelists arguing against the increase in nanotechnology funding. The instructor takes a back seat during the entire hearing, and only acts as a facilitator and timekeeper. Students are graded on their individual presentation, their ability to ask (and/or answer) questions, the quality of the team’s written summary, and a self/peer evaluation.

Finally, when it comes to the final exam, one way to assess students on their understanding of the core content and demonstrate creativity at the same time is to require them to write an original research proposal. With discussions about funding, peer review, and recent advances occurring at various times during the semester, students have been presented with the tools to come up with their own unique idea and put it forth in the form of a formal research proposal. As an additional exercise prior to the final assignment, students are assigned past proposals and asked to “peer review” them according to NIH/NSF guidelines. This allows them to see sample proposals and appreciate the importance of their final assignment.

5. Assessment

Assessment data for each iteration of this course has been collected through the end-of-semester IDEA forms that Susquehanna University uses to evaluate teaching effectiveness and student progress on relevant objectives. Relevant objectives are selected by the faculty member and students rate their progress on these objectives, in addition to rating the course and the instructor. Table 2 shows the relevant objectives selected each time, and the average student rating, in addition to how the students rated the course itself. Objectives that were not relevant to the course are not included below.

While the IDEA forms do not directly assess each individual Central Curriculum learning goal, students are able to reflect on how much they have learned and connect it to their respective disciplines. Also, learning how to find and use resources is a very important skill that students must develop, and a special topics course is an appropriate venue for that. Of course, students use outside resources in all courses, especially when writing laboratory reports. However, the key difference here is that for most of the Nanoscience assignments, they are seeking out information on topics that they are individually most interested in, whether it is for a presentation or final research proposal.

Table 2. Summary of Course Evaluations. Students rated using a scale of 1-5, where 5 corresponds to “Strongly Agree”. Ratings in *italics* were in categories not included as a relevant objective that year. (F = Fall, S = Spring)

Semester	F2006	F2008	S2013	F2015	S2019	F2021
Total Enrolment	10	7	9	12	8	18
Excellent Course	3.8	4.7	4.7	4.2	4.7	4.8
Progress on Relevant Objectives						
Gaining factual knowledge	3.9	4.9	4.9	4.3	4.3	4.5
Learning fundamental principles ¹	3.5	5.0	4.4	4.5	n/a	
Developing specific skills and competencies	3.4	5.0	4.3	3.9	4.1	3.8
Developing creative capacities	3.0	4.4	3.3	2.4	2.1	2.6
Developing skill in oral and written expression	3.4	4.9	4.0	3.5	3.9	3.5
Learning how to find and use resources	3.5	5.0	4.4	4.2	4.3	3.8

¹ Objective merged with “gaining factual knowledge” in the revised IDEA forms.

Qualitative feedback is also requested at the end of the semester, and occasionally mid-semester. Students have consistently been very positive about their experience and have offered helpful suggestions, both at mid-semester, and at the end of the course. One question that is typically asked mid-semester is “list three topics you would like to learn more about”, and the top three are usually biomedical applications, potential environmental/health concerns, and everyday uses. The mid-semester feedback has been used to adjust the lectures and the choice of topics for the “Nano in the News” segments.

6. Conclusion

In conclusion, a current and exciting course in nanoscience can be successfully incorporated into the curriculum at a PUI and generate significant student interest. In addition to the review of basic concepts from introductory chemistry, biology, and physics, the topics and approaches to introduce them (Nano in the News), activities like the senate hearing, and assessments can be selected to generate maximum engagement and positive outcomes for students and faculty alike. The course can be successful even without access to high-end instrumentation. While some aspects of course design are common, student input and instructor flexibility can make the course successful for everyone, without compromising learning goals. Faculty presentations on the topic can also serve as an excellent recruiting tool as nanoscience is a broad field that can be presented in a way that interests science students with diverse backgrounds and career goals. And finally, as shown more recently, nanotechnology education need not be solely in the

domain of post-secondary education. It can also be introduced at the pre-college and even early childhood level to help enhance literacy of the field [34,35].

Supplementary Information

Course syllabus, presentation guidelines, and debate guidelines are available upon request.

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