

## **Assessing the Impact of a Flipped Classroom Approach in a Multidisciplinary Undergraduate Nanotechnology Course**

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Mehmet C. Ozturk received his BS degree in Electrical Engineering from Bogazici University in Istanbul, Turkey in 1980. He received his MS degree from Michigan Tech in 1983 and his PhD degree from NC State University in 1988. Immediately after graduation, he joined the faculty in the Department of Electrical and Computer Engineering. Since 2008, Dr. Ozturk has been serving as the director of the NCSU Nanofabrication Facility, which operates as the central laboratory for the entire University. In 2012, he became the education and diversity director of the NSF sponsored ASSIST Nanosystems Engineering Research Center. In 2015, he has started serving as the deputy director of the same center. Dr. Ozturk's research interests center around innovations in engineering education, nano-materials/processes and flexible energy harvesting technologies. In the ASSIST center, he is leading a research group working on thermoelectric energy harvesting for self-powered body wearable sensors for health and environmental monitoring. He was named a fellow of IEEE for his contributions in Si and SiGe Epitaxy and their applications in advanced MOS field effect transistors.

# Assessing the Impact of a Flipped Classroom Approach on Student Performance in a Multidisciplinary Undergraduate Nano-Technology Course.

## Introduction

The flipped classroom approach has received significant attention in the literature in recent years, with numerous publications on several variations of this concept. Broadly, this approach is understood to mean swapping the traditionally in-class lecture with the out-of class activities like problem solving and projects. Generally this means students are assigned some form of online or video lectures to watch at home, opening up class time for a variety of active and/or collaborative learning experiences.

Despite the fact that the term “flipped classroom” has been around for some years, several surveys of the literature conclude that there is a need for further research in this area.<sup>1-3</sup> This is due in part to the fact that instructor implementation of this educational model varies widely, meaning there is not one consistent model for instructors to follow.<sup>1</sup> Both the types of in-class activities and the formats for out-of-class lectures can look very different from course to course and from instructor to instructor. This makes assessment of the impacts of the model quite difficult, resulting in relatively little research evidence of student performance in a flipped classroom versus a traditional one.<sup>1-3</sup>

In the following narrative, we will describe one implementation of a flipped classroom, highlighting some unique aspects of the course itself and why it is well suited for the flipped model. Key features of both the in-class and out-of-class activities will be presented. Finally, we will show some preliminary comparisons of both student perceptions and actual student performance between the flipped and traditional versions of the course.

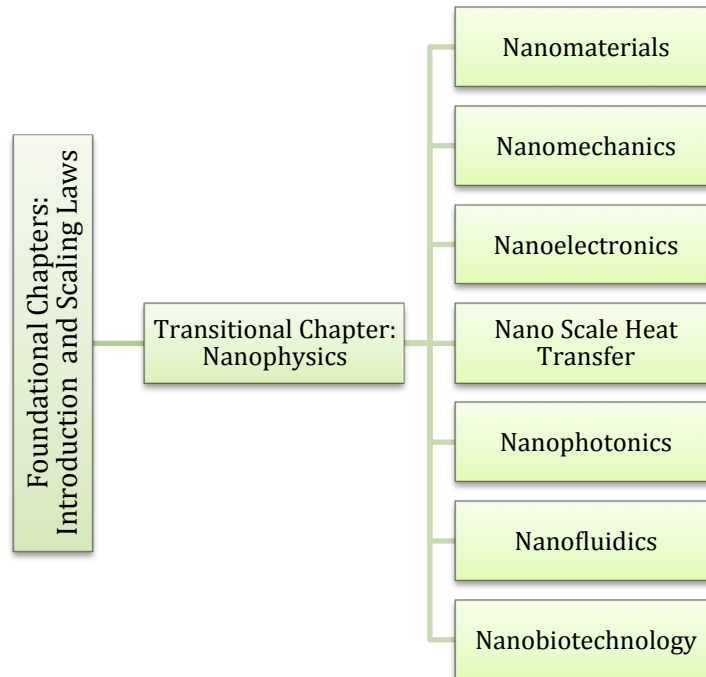
## Course Overview

“Introduction to Nano Science and Technology” serves as the foundational course for a multidisciplinary minor program in Nano-Science and Technology<sup>4</sup> developed at the Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST) Center. This is a multidisciplinary course listed under the College of Engineering, and therefore not belonging to any specific department. Students from any engineering discipline are encouraged to take this course to learn about nanotechnology in general, but also applications relevant to the specific disciplines.

The course provides an introduction to the physical principles of materials and structures at the nano-scale and how these principles are connected to exciting applications in different fields such as nanoelectronics in electrical engineering, nanofluidics in mechanical engineering, or nano-biotechnology in biomedical engineering. The course textbook, titled *Nanotechnology: Understanding Small Systems*, highlights these various applications effectively for a multidisciplinary classroom.<sup>5</sup> To underscore the multidisciplinary nature of the minor, the course is listed as a general engineering (E) course under the college of engineering as opposed to cross-

listing the course among multiple departments. It is important to note that our students at our university are familiar with this practice due to a required first year course entitled E101 *Introduction to Engineering and Problem Solving*. The course prerequisites are satisfied by all engineering disciplines through completion of the physics and the calculus sequence during the second year.

An overview of the course structure is provided in Figure 1. The course begins with two foundational chapters defining what nanotechnology is, providing the key historical milestones and introducing the basic concepts of scaling and miniaturization. The third topic, nanophysics, is a transitional chapter that delves into the current understanding of the atom, including electron orbitals and quantum numbers. This chapter provides the background instruction needed for students from all engineering backgrounds to be able to understand the seven application chapters that follow.



**Figure 1: Course Structure and Organization by Topic Area**

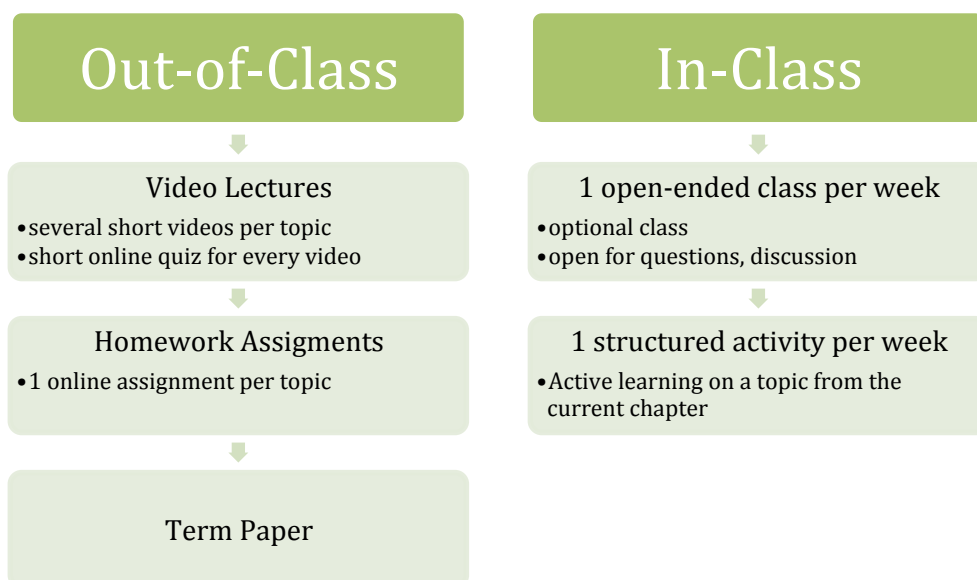
The remainder of the course is broken up into seven different application areas. The engineering disciplines represented include mechanics, electronics, heat transfer, fluidics, photonics, and biotechnology, making the course relevant to students coming from a variety of backgrounds. The learning objectives for each of the course topics are given below. These objectives fall in one of the following categories: concept, calculation/estimate, measurement or fabrication tool, device or structure, technology at the state of the art, history, and skill (e.g., technical writing, critical evaluation, etc.)

1. Introduction and Scaling Laws
  - a. Define the term “nanotechnology” and discuss potential impact, challenges, and risks.
  - b. Recall the historical milestones in the development of nanotechnology, including contributions of key figures like Richard Feynman.
  - c. Estimate how the characteristics of a system will change as its dimensions change using common scaling laws.
2. Nanophysics
  - a. Recall the key historical insights needed to reach our current understanding of atoms, electrons, and photons, including the specific contributions of Max Planck and Albert Einstein.
  - b. Describe the structure of atoms, including electron orbitals and quantum numbers.
  - c. Calculate the quantized energy levels of electrons within an atom and the energy/wavelength/momentum of photons, and apply the principles governing when energy can transfer from one to another.
  - d. Describe the famous experiments showing the photoelectric effect and wave/particle duality of electrons (i.e., double-slit), and explain why the behavior observed cannot be explained by classical physics.
  - e. Explain and apply Heisenberg’s uncertainty principle.
  - f. Calculate the allowed quantized energy levels, wave function, and probability density functions of an electron in an infinite potential well (i.e., a particle-in-a-box, or, quantum confinement).
3. Nanomaterials
  - a. Describe the four types of chemical bonds (i.e., ionic, covalent, metallic, van der Waals), identify under what conditions each one can occur, and estimate their relative bonding strengths in general.
  - b. Discuss the structures into which atoms can be arranged in a bulk solid (i.e., crystalline, polycrystalline, and amorphous).
  - c. Classify nanostructures according to their types (i.e., particles, wires, layers, self-assembled-monolayers, and micelles).
  - d. Describe the structure, key properties, and history of discovery of carbon nanostructures, including carbon nanotubes, spherical fullerenes, and graphene.
  - e. Evaluate the potential impact, challenges, and risks of at least one start-of-the-art application of nanomaterials.
  - f. Recognize the terminology of, identify the utility, and explain the crystal growth/deposition techniques (i.e., PVD, CVD, MBE, ALD, etc.), and the primary carbon nanostructure synthesis methods that enable atomic-scale control of materials.
  - g. Explain how X-ray diffraction characterization techniques are used to determine atomic structure, and calculate simple cases.
4. Nanomechanics
  - a. Analyze the oscillation behavior of a cantilever beam, including its frequency, forces, and energy, given geometry, material, damping, and boundary information.
  - b. Calculate the oscillation behavior of a pair of atoms, including their frequency, forces, and discrete energy levels, given mass, geometry, and boundary information.

- c. Employ wavefunctions and probability density functions to explain why energy levels are quantized in atom pairs.
  - d. Define acoustical and optical phonons, and discuss their vibrational energy and propagation behavior.
  - e. Evaluate the potential impact, challenges, and risks of at least one start-of-the-art application of nanomechanics.
  - f. Explain the operational principles of scanning probe microscopes, including the Scanning Tunneling Microscope (STM) and the Atomic Force Microscope (AFM).
5. Nanoelectronics
- a. Explain how energy bands form from discrete energy levels in atomic orbitals.
  - b. Define band gap, conduction band, valence band, the Fermi level, and an exciton.
  - c. Calculate the energy difference between sublevels for nanoparticles (i.e., quantum dots) with finite numbers of atoms, and use this to identify the behavior and properties of electrons at a given temperature.
  - d. Identify the conditions under which electron tunneling may occur, within infinite and finite potential wells.
  - e. Discuss the differences between electronic behavior in nanoparticles formed with metals or semiconductor materials, and in individual or ensembles of molecules.
  - f. Evaluate the potential impact, challenges, and risks of at least one start-of-the-art application of nanoelectronics.
  - g. Demonstrate through sketches and written explanation the structure and basic operational principles of key electronic devices, including PN junction, MOSFET, single electron transistor (SET), and FINFET.
  - h. Explain the operational principles of the key semiconductor fabrication processes, including photolithography, implantation, vapor deposition, etching, etc.
6. Nanoscale Heat Transfer
- a. Define heat and explain the three modes of heat transfer: conduction, convection and radiation.
  - b. Explain how heat is *conducted*, in metals, semiconductors, and insulators, via phonons, electrons, atoms, and molecules.
  - c. Calculate the thermal resistance of an object with a known thermal conductivity, and physical dimensions; Use this resistance to calculate the heat conducted through the object for a given temperature differential.
  - d. Explain how a thermoelectric cooler / harvester works using the energy band diagram for electrons.
  - e. Explain the Seebeck coefficient, Peltier effects, and ZT figure of merit.
  - f. Calculate the output voltage and power of a thermoelectric generator given the Seebeck coefficient, electrical resistivity, temperature differential and the number of legs, and explain why semiconductors are better for this application compared to metals and insulators (i.e., regarding phonons vs. electrons).
  - g. Explain how reducing the dimensions contribute to the performance of thermoelectric devices, including addressing how the importance of the mean-free-path changes at the nanoscale.

- h. Evaluate the potential impact, challenges, and risks of at least one start-of-the-art application of nanoscale thermoelectrics.
7. Nanophotonics
  - a. Explain how photons interact with materials generally, including absorption, emission, scattering, and reflection, and the concept of permittivity.
  - b. Calculate the plasma frequency and permittivity of metal conductors, and explain its influence on the photonic properties of metals.
  - c. Describe how the size of a quantum dot affects its electronic band gap, and calculate the impact on its photon emission, for both metals and semiconductors.
  - d. Explain what are near-field optical microscopes and how they overcome the classical resolution limits of microscopes.
  - e. Evaluate the potential impact, challenges, and risks of at least one start-of-the-art application of nanophotonics (including plasmonics, photonic crystals, and nanoparticles in organic photo-voltaics)
8. Nanofluidics
  - a. Distinguish when an object within a fluid is within a low Reynolds number condition.
  - b. Describe the impact of Brownian motion and low Reynolds numbers on nanoscale objects.
  - c. Explain how surface charges at interfaces of ionic fluids and surfaces influences their ability to influence fluid flow and promote or inhibit liquid adhesion (e.g., water or photoresist).
  - d. Explain how the ionic double layer, nanoscale channels, and an electric field can be configured into a nonmechanical fluid pump.
  - e. Evaluate the potential impact, challenges, and risks of at least one start-of-the-art application of nanofluidics.
9. Nanobiotechnology
  - a. Describe the structure and function of the four molecular families of major cellular machinery: sugars, fatty acids, nucleotides, and amino acids.
  - b. Describe how information is stored, copied, and recovered in cells.
  - c. Describe how energy is generated, stored, recovered.
  - d. Sketch and explain how molecular motors in muscles work.
  - e. Discuss the importance partial order and self-assembly in cellular.
  - f. Evaluate the potential impact, challenges, and risks of at least one start-of-the-art application of nanobiotechnology.

Because this course focuses on applications of nanotechnology in a variety of academic disciplines and has a multidisciplinary student composition, we believe it to be uniquely suited to work in a flipped classroom format. In the following sections we will detail the course activities, both in-class and out-of-class. An overview of these activities is given in Figure 2.



**Figure 2: Summary of course format including all in-class and out-of class activities**

### Out-of-Class Activities

Recent research in this area seems to indicate that simply having video lectures may neither improve or hinder student learning.<sup>1</sup> It is the added active-learning activities that can be done in class in lieu of lecture that seem to provide added value. However, we propose that in the case of highly multidisciplinary areas with high research activity, video lectures can provide certain advantages.

For this course specifically, the lectures are recorded by a number of professors representing the various research areas within the field of nanoscience. For example, a mechanical engineering professor whose research area lines up with the course content can record the nanomechanics lectures. Similarly, the bio-nanotechnology lectures can be recorded by a biomedical engineering faculty member with expertise in the field. This way students benefit from a variety of lecture styles and the expertise of several instructors at once. Once the lectures are recorded and posted online, they can be used semester after semester by any course instructor. This approach also allows the flexibility to edit and/or substitute lectures over time as new technologies or topics appear that can be added to the curriculum.

The recorded lectures are then used in conjunction with targeted active learning sessions in the classroom. In this way, students benefit from the combined expertise and unique perspectives of a variety of lecturers, tied together through the in-class activities and assignments led by the course instructor. The course instructor in this case takes on the role of facilitator having a broad understanding of the subject matter, without needing to be a content area expert in every possible application of nanoscience. More importantly, the instructor can rotate semester-to-semester while maintaining uniformity in the course delivery.

This format paves the way for broader dissemination of this course to our partner schools and community colleges who may be interested in offering a course in nano-science and technology

but do not have the local expertise in all of the application areas. The expert-recorded lectures and course materials can be packaged, and a local instructor having a general technical background can be trained to serve as facilitator.

A few common guidelines were implemented to maintain some uniformity despite the fact that different individuals record lectures. All videos are purposefully short (usually less than 20 minutes) and are never simply a narrated PowerPoint presentation. In addition, each lecture video is accompanied by a short (1-2 question) quiz designed to test the student's retention of the material.

It is important to note that the course consists of two other components in addition to the video lectures and in-class activities. First, there are weekly, online, homework assignments. These are composed of a variety of different types of questions including multiple choice, short answer, and calculation. These homeworks are meant to test student's understanding of all the course material including online lectures, in-class activities, and reading assignments from the textbook. The second main component is an individual term paper that explores a nano-science topic of the student's choice. Students are asked to pick a topic relevant to the course and conduct a literature review on that topic.

### In-Class Activities

There are two 75-minute in-class sessions scheduled for this course each week during a normal semester. One of these sessions was designated as an open question and answer session. During this class students were encouraged to bring their homework problems or any other questions to discuss as a group and with the course instructor. This was an optional and completely open-ended class.

The second of the weekly class meetings was a required, structured, active and collaborative learning session. Each week the structured activity explored a key concept or topic covered in the video lectures. These activities had various formats including: individual and group problem solving, individual and group quizzes, think-pair-share activities, hands-on laboratory style activities, group presentations, and tours of relevant campus facilities. A few specific examples are detailed here:

- **Literature Review:** In this activity, the instructor collects a set of recent journal publications relevant to a specific topic being covered in the lecture. The class is divided into small groups (3-4 students). Each group is tasked with reading and analyzing one or two papers and presenting their findings to the class. The breadth and depth of this activity can vary as desired. For instance, the instructor may want the students to get a broad view of the different research directions in a field like nano-biotechnology. In this case the students would be provided a large range of articles and given an option about which to explore. Alternatively, the goal may be for students to understand how nanotechnology is impacting a specific application like improving solar cell efficiency, in which case perhaps 3-4 key papers would be targeted.



- **Hands On Lab:** In some cases, simple hands-on visualization tools can be adapted even to a large classroom without benefit of a laboratory setup. In this specific case the students explored crystal structures using a very inexpensive gumdrop and toothpick model. Working in small groups they explored the various Bravais Lattices as well as graphene sheets and nanotubes. This visualization helped solidify students' understanding of these structures as well as the importance of the Surface Area to Volume relationship.
- **Think-Pair-Share and Guided Problem Solving:** In these activities students were given sample homework and exam problems, with multi-step problems broken down into simpler components. Students are given a few minutes to think on their own, then are encouraged to solve the problems together with a partner, and finally groups are invited to share solutions. Throughout the process, the instructor actively engages with individuals to answer questions and provide guidance.

### Preliminary Results and Analysis

This course has been taught every semester beginning in the Fall 2013 semester with full enrollment (approximately 60 students per semester). In the Fall 2015 semester, the flipped classroom concept was introduced for the first time. Here we will present a comparison between the Fall 2014 (traditional) and Fall 2015 (flipped) sections of the class. These two sections are chosen because they were very similar in many ways, allowing for a more valid comparison. The two sections had similar enrollment (~60 students) from a fairly similar cross-section of engineering departments. Both sections used the same textbook and covered the same chapters in the same order. The homework assignments and term paper assignment were identical. While the 2015 section was taught by a different instructor, several of the video lectures were provided by the 2014 instructor, creating some consistency in instruction. The primary difference between the sections was the classroom flip.

Both class sections received nearly identical final exams so results could be compared objectively. On six of the eight identical exam questions (See Table 1), the average scores of both sections were very similar. Statistical analysis was performed on the scores for a two-tailed hypothesis at a significance level of 0.05. For this analysis, a p-value of less than 0.05 suggests strong evidence against the null hypothesis, in this case that the two sets of scores are equivalent. The calculated p-values (given in Table 1) indicate that the scores between the two sections were only different by a statistically significant margin on two of the eight exam problems.

It is important to note that both sections performed equally well on all calculation questions. Of the two recall questions, the flipped classroom scored slightly better on one, and the traditional scored slightly better on the second, but not to a statistically significant level ( $p=0.07$  and  $p=0.12$ ). The only statistically significant score discrepancies exist for the open-ended responses ( $p<0.05$ ). Some of this variation can be attributed to discrepancies and subjectivity in grading from one semester to the other.

**Table 1: Comparison of exam results by question**

Question Text	Category	Difference between flipped and standard results
Suppose a conduction electron in a quantum dot emits a photon with frequency of 600 THz as it drops to the valence band. Determine its band gap in units of both J and eV.	Calculation	not statistically significant p=0.68
Calculate the Reynolds number of a 100 nm diameter spherical fullerene (i.e., buckyball) falling by gravity at 1 m/s in air (density = 1.23 kg/m <sup>3</sup> , viscosity = 1.72 x 10 <sup>-5</sup> Pa-s).	Calculation	not statistically significant p=0.81
Name and describe the four molecular families into which we can group the thousands of different kinds of molecules in a cell. Include their primary functions within nanobiotechnology, and if possible, a description of their molecular features.	Recall: Short Answer	not statistically significant p=0.07
Indicate if the following are True or False: (sample items) a) _____ Photons have energy and velocity, but no momentum or mass. b) _____ The inertial terms in the Navier-Stokes equations can be neglected when the Reynolds number is very small – this means that the viscous forces are stronger than the inertial forces.	Recall: True/False	not statistically significant p=0.12
What is the most surprising aspect (to you) of nanotechnology that you learned in this course? Explain this aspect in detail – it can be a device, structure, phenomena, etc.	Open-ended explanation	not statistically significant p=0.79
Consider the scope of all the topics in the class related to nanotechnology. Describe one way that (nanoscale) quantum confinement improves the performance of any mechanical, electronic, photonic, thermoelectric, fluidic, or biological system of your choice. You may use words and/or sketches.	Open-Ended Explanation	Flipped outperformed (Statistically significant at p<0.05)
Through words and sketches, explain how near-field imaging works in general. Include a specific reason for why this approach can overcome the resolution limit imposed by the Rayleigh criterion, so that feature sizes on the scale of 10s of nm can be imaged with optical wavelengths of 100s of nm.	Open-ended explanation	Traditional outperformed (Statistically significant at p<0.05)
Through words and sketches, describe the phenomena known as electroosmosis, and how it can be used to implement a nanofluidic pump:	Open-ended explanation	not statistically significant p=0.21

Eight identical, online, homeworks with automated grading were assigned. In order to minimize the possibility of students sharing solutions from one semester to the next, the homework is computerized. Although the problems are the same, the program automatically generates new values for every instance of the homework that is initiated. In addition, detailed solutions are not broadcast for these assignments. The percent difference between the overall homework averages in both sections was only 1.4%. This is not a statistically significant difference (p=0.37). When looking at individual assignments, the percent difference in average scores varied between 2%

and 11%. The flipped section did better on some assignments and the traditional excelled in others. The only statistically significant ( $p < 0.05$ ) discrepancies occurred for HW assignments 1, 5, and 7. These assignments correlate to the introductory chapters, the nano-scale heat transfer, and the nanofluidics chapters.

Finally, student perceptions regarding the course were analyzed, comparing the two class sections. The students were asked to open-endedly comment on the strengths and weaknesses of the course, the instructor, and to provide any other comments or suggestions.

Twenty-four individual comments were provided by students in the traditional section (this represented a 34% response rate). The most common theme among these was related to the breadth and quantity of information in the course. The comments were both positive and negative (in equal proportion). In one case, a student noted that the instructor did not have expertise in all of the topic areas. The second most common theme related to the need for more in-class examples, test-preparation, explanation, and question/answer sessions. All of these comments suggested that students would have benefited from more of these types of activities. Overall, these comments lead us to believe that this course could benefit from being flipped for two main reasons: (i) online lectures by different professors would allow more efficient transfer of the large amounts of information to students, and (ii) the flipped environment would allow class time for examples and explanations that the students are interested in.

Forty individual comments were provided by students in the flipped section (this represented a 44% response rate). The most common theme among these comments was simply whether or not the student liked the flipped class model. Of 14 such comments, eight indicated that they liked the flipped class. Of the 6 negative comments, a majority cited concerns with the types of in-class activities as the main reason for their comment. The second most common theme related to the types of in-class activities (17 responses). Overall, students seemed to respond positively to the problem-solving activities, but failed to see the benefit in the other types of activities.

Based on the comparison of student performance on tests and homeworks (as detailed above), we do not observe a statistically significant difference in scores between the flipped and traditional classroom. Students performed equally well on homework assignments and exam questions. Also, students made very few comments regarding the quality or usefulness of the video lectures. Therefore, overall, we can conclude that the video lectures themselves did not have a significant impact on student learning. This result is in agreement with findings in literature.<sup>1</sup> However, when taking into account the most common student comments, we see a great opportunity and potential for improving student performance in future implementations of the flipped class. The majority of student concerns about the flipped course referred to the in-class activities. The majority of student concerns about the traditional course also referred to the need for more in-class activities (not lectures). Therefore, in future work we will focus our efforts on the specific types and content of the in-class activities. Different types of activities engage students with different learning styles, while the course content covered in the activity must directly relate to the most critical learning objectives.

## Conclusions

“Introduction to Nano Science and Technology” is a unique course providing a broad introduction to fundamental concepts of nanoscience and technology while emphasizing the multidisciplinary nature of the field. Because this course focuses on applications of nanotechnology in a variety of academic disciplines, we believe it to be uniquely suited to work in a flipped classroom format. In this implementation of the flipped model, lectures are recorded by several professors representing the various application areas. The perspectives of these different lecturers are tied together through the in-class activities and assignments led by the course instructor.

This study compared two sections of the course, one traditional and one flipped, in order to explore the impact of the flipped class model. The learning objectives, course textbook, and range of topics covered have remained constant. Identical homework assignments and exam questions were used to evaluate student performance in each section. In summary, student performance on exams and homeworks was equivalent between the two sections. However, based on student comments provided in course evaluations, we conclude that optimizing the in-class activities will likely improve student performance, allowing the flipped model to give superior outcomes in future iterations of the course.

## References

1. DeLozier, S. J., & Rhodes, M. G. (2016). Flipped Classrooms: a Review of Key Ideas and Recommendations for Practice. *Educational Psychology Review*.
2. Bishop, J. L., & Verleger, M. A. (2013). The Flipped Classroom: A Survey of the Research. In *ASEE Annual Conference and Exposition, Conference Proceedings*. American Society for Engineering Education.
3. Zuber, W. J., (2016). The flipped classroom, a review of the literature. *Industrial and Commercial Training*, Vol. 48, Nr. 2, pp. 97-103.
4. Veety, E. N., Ozturk, M. C., Escuti, M., Muth, J., & Misra, V. (2014). Multidisciplinary undergraduate minor program in nano-science and technology at North Carolina state university. In *ASEE Annual Conference and Exposition, Conference Proceedings*. American Society for Engineering Education.
5. Rogers, B. L., Adams, J., & Pennathur, S. (2014). *Nanotechnology: Understanding Small Systems*, Third Edition. CRC Press.