January 2003

A Course in Micro- and Nanoscale Mechanics

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NOTE: At the time of publication, author Robert W. Carpick was affiliated with the University of Wisconsin. Currently July 2007, he is a faculty member in the Department of Mechanical Engineering and Applied Mechanics at the University of Pennsylvania.

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Abstract

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Comments

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A Course in Micro- and Nanoscale Mechanics

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Abstract

At small scales, mechanics enters a new regime where the role of surfaces, interfaces, defects, material property variations, and quantum effects play more dominant roles. A new course in nanoscale mechanics for engineering students was recently taught at the University of Wisconsin - Madison. This course provided an introduction to nanoscale engineering with a direct focus on the critical role that mechanics needs to play in this developing area. The limits of continuum mechanics were presented as well as newly developed mechanics theories and experiments tailored to study and describe micro- and nano-scale phenomena. Numerous demonstrations and experiments were used throughout the course, including synthesis and fabrication techniques for creating nanostructured materials, bubble raft models to demonstrate size scale effects in thin film structures, and a laboratory project to construct a nanofilter device. A primary focus of this paper is the laboratory content of this course, which includes an integrated series of laboratory modules utilizing atomic force microscopy, self-assembled monolayer deposition, and microfluidic technology.

Introduction

Nanoscale science and technology are inspiring a new industrial revolution that some predict will rival the development of the automobile and the introduction of the personal computer.[1] By observing and manipulating materials at the nanoscale, researchers have been able to develop new materials with novel and extreme properties. These properties have been optimized and exploited, allowing industry to realize nanotechnology-based consumer products, such as light-emitting diodes (LEDs), and computer hard disks. Because of the diversity of disciplines pursuing research and applications in nanoscale science and engineering, nanotechnology has the potential to make an even broader impact.[2]

The importance of this emerging technology to society and industry requires that undergraduate institutions take steps to adapt their curriculum to ensure a capable future workforce as well as a more scientifically literate general population.[3-5] Problem-solving will continue to be an important part of undergraduate education, as will the need to cultivate creative, critical, and entrepreneurial thinking.[4,6] Yet, science and engineering undergraduates will need a comprehensive education that includes nanotechnology in order to navigate successfully the challenges of the 21st century. Students need an interdisciplinary education in the basic sciences, the engineering sciences, and the information sciences, as well as an understanding of the relationships of these fields to nanotechnology. The interdisciplinary nature of nanotechnology is both a benefit and a challenge as faculty balance between the breadth and depth of course work in order to develop a technically-trained workforce.[4,5]

The challenge of integrating nanotechnology into the curriculum is being met by a number of colleges and universities. In recent years, numerous education and outreach efforts have been developed to educate and inform students and the general public about nanotechnology.[7,8] In addition, courses in nanotechnology have begun to appear in college catalogs, and nanotechnology concepts have been incorporated into undergraduate general chemistry and physics courses.[4] Universities that now offer courses with a significant component dedicated to nanotechnology include, for example, the University of Notre Dame (*Electrical Engineering 666: Advanced Quantum Devices*), Rice University (*Chemistry 533: Nanostructures and Nanotechnologies I*), Renssaleaer Polytechnic Institute (*Materials Science and Engineering: Nanostructured Materials*), the University of Washington Integrative Graduate Education and Research Training (IGERT) (*Bioengineering 583 or Chemistry 560C: Frontiers in Nanotechnology*), and the University of Wisconsin-Madison (*Chemistry 801: Nanostructured Materials and Interfaces* and *Physics 801: Nanostructures in Science and Technology*).[9] There are also numerous efforts abroad, as is exemplified by a Bachelors and Masters programs in Nanotechnology initiated by The University of Basel (Switzerland) and a Masters Training Package in Nanoscale Science and Technology offered jointly by the University of Leeds and University of Sheffield (United Kingdom).

This paper describes a new nanotechnology course in the Department of Engineering Physics at the University of Wisconsin – Madison (Figure 1). This course, entitled, "Micro- and Nanoscale Mechanics," is designed to introduce students to mechanics when practiced on the microscale and nanoscale with an emphasis on the interdisciplinary nature of nanoscale science and engineering. Traditional approaches to engineering education, including lectures, homework assignments, and laboratory experiments, are combined with reflective writing assignments and the submission of a nanotechnology review article to a simulated peer-reviewed journal edited by the instructors and other students in the course. These activities are seamlessly integrated into the course providing a coherent, multi-faceted structure for the education of the students enrolled in the course.


Spring 2003
Micro- and Nanoscale Mechanics
Instructors: W.C. Crone and R.W. Carpick
Tue./Thurs. 11:00-12:15p
EMA 601 (Lecture 3)
Class #51123
3 credits

Course Description:

This course will provide an introduction to nanoscale engineering with a direct focus on the critical role that mechanics needs to play in this developing area. Engineering is progressing to ever-smaller scales, enabling new technologies, materials, devices, and applications. Mechanics enters a new regime where the role of surfaces, interfaces, defects, material property variations, and quantum effects play more dominant roles. We will discuss how mechanics becomes integrated with the fields of materials science, chemistry, physics, and biology at this scale. We will cover a variety of concepts and applications, drawing connections to both established and new mechanics approaches. We will discuss the limits of continuum mechanics and present newly developed mechanics theories and experiments tailored to describe micro- and nano-scale phenomena. We will emphasize specific applications throughout the course.

Prerequisites:

Students should have a general understanding of mechanics and materials, and a deep curiosity in extending their knowledge beyond traditional bounds. This course is open to graduate students and advanced undergraduates, but it is designed for students willing and able to work at least at the level of a first year graduate student. Literature reviews, critical peer discussion, and student presentations will be an integral part of the course.

Course Web Page:

http://www.engr.wisc.edu/ep/ema/courses/ema601micronano.html

Figure 1. Course announcement for the Micro- and Nanoscale Mechanics course offered at UW-Madison in Spring 2003.

Course Description

This graduate/senior undergraduate level course provided an introduction to nanoscale engineering with a direct focus on the critical role that mechanics needs to play in this developing area. The first offering of this course in the Spring semester of 2003 drew students from a variety of backgrounds including. The vast majority of undergraduates enrolled were juniors and seniors majoring in Engineering Mechanics. Graduate student backgrounds included Engineering Mechanics, Materials Science, Chemical Engineering, Physics, and Civil and Environmental Engineering. A total of 26 students took the course, approximately one-third of whom were undergraduates. In response to a survey handed out on the first day of class, students responded that they hoped to learn about "nanoscience basics," "mechanics of small scale structures," and "variation of properties as size of structures decreases." In the broader view, students were interested in gaining deeper fundamental knowledge in mechanics, exploring future technology, and applying what they have learned to current and future research projects. The majority of the graduate students in the class were pursuing a PhD and the majority of the undergraduates were interested in continuing their education in an engineering graduate program after completing their BS.

The content of the course was designed to introduce students to micro/nanotechnology and provide them with a basic understanding of how mechanics is treated at the nanoscale with discussions on current and potential applications. Also, with micro/nanotechnology being an inherently interdisciplinary topic, the course included overview of micro/nanotechnology, mechanics concepts, synthesis techniques, and materials properties. These overviews lead into more in-depth discussion of various aspects of nanotechnology as it relates to mechanics. These include surface characterization and surface forces, particularly as applied to scanning probe microscopy (SPM) and microelectromechanical systems (MEMS), theoretical and computational techniques for modeling nanoscale systems, and the applicability of traditional macroscale mechanics concepts to nanoscale systems. The lecture topics for the course are given in Table 1. Along with two 75-minute lectures per week, numerous demonstrations and experiments were used throughout the course, including synthesis and fabrication techniques for creating nanostructured materials, and bubble raft models to demonstrate scale effects in thin film structures.

To address ABET broader impacts, an activity adapted from the education and outreach resources of the University of Wisconsin Materials Research Science and Engineering Center (MRSEC) on nanostructured materials and interfaces was used to explore the potential societal implications of nanotechnology (http://www.mrsec.wisc.edu/edetc/IPSE/activities.html). Students are asked to imagine a future in which medical nanobots exist. The students discuss the proposed incorporation of nanobots into medical care by splitting into five groups, each group representing a specific segment of the population (U.S. Government, Nanobot Manufacturer, Insurance Companies, Health Care Workers, and Patients). Members from each team roleplay to explain why they believe nanobots should or should not be used. Although this activity was originally created for K-12 audiences, the undergraduate and graduate students in the course were overwhelmingly positive about the activity and its usefulness in encouraging them to consider the potential implications of new technologies.

Lecture No.	Topic
1	Introduction to nanotechnology
2	Overview of new opportunities and connections to mechanics
3-4	Overview of mechanics of materials and elasticity
5	Atomic structure of materials, defects and dislocations
6-7	Surface characterization techniques
8	Introduction to nanoscale modeling
9-10	Phase transformations and shape memory materials - size and phase transformation in smart materials - melting point depression and nanophase diagrams
11-12	Overview of synthesis techniques
13-18	Mechanical testing and material property determination at small scales, topics such as - applying load to small scale structures - measuring strain on small scale structures - cantilever deflection as a sensor technique - size-scale strength effects - impact of size on thin film ductility and fracture - capillary forces and tall walls
19-21	Scanning probe techniques - AFM - atomic scale studies of friction and adhesion
22-25	Using mechanics in micromachines (MEMS): - applications, design, performance, and testing - the issue of tribology in traditional MEMS - soft MEMS architectures (fluid mixing, adhesion and membrane forces)
26	Nano-bio-mechanics
27-28	Nanocomposites
29-30	Theory, modeling, and computational techniques for mechanics modeling of nano-systems including MD of fracture mechanics, mixed atomistic/continuum modeling of sliding friction

Table 1. Topic covered in 75-minute lectures for *Micro- and Nanoscale Mechanics*.

One assessment technique used in this course was the reflective writing assignment. Each week students were asked to respond to a question related to the week's lecture. For example:

> *Week #3 Pick an experimental technique that is used to characterize surfaces that was not discussed in detail in Thursday's lecture. Provide a brief description of what the technique can measure, how it works, and why it is a useful tool (e.g. important scientific insights gained, or applications that can be addressed).*
>
> *Week #8. In class we have talked about how tension and bending at the micro- and nanoscales is used to characterize materials, guard against or prevent damage to a device, and create a device. Use the internet or the library to find an application of torsion to micro- and nano-scale devices.*

These reflective writing assignments were intended to prompt students to evaluate information, draw inferences, identify cause and effect, and draw comparisons with examples from the literature. The responses were posted by students in a web-page forum accessible to the entire class. Participation by the students was very high and some limited dialog between fellow students was generated. Generally the submitted responses were well-written and creative. The task appeared to be one that consistently engaged the students.

In addition to the classroom activities, which include traditional lectures as well as demonstrations and small-group activities, there is a significant laboratory component to the course. The laboratory activities are self-contained modules which build upon each other culminating in the production of a microfluidic device for the filtration of nanoparticles by the conclusion of the course. The individual modules are designed to coincide with the subject matter under discussion in the course such as surface characterization, synthesis techniques, and soft MEMS. These modules utilize web-based lab procedures which were developed through the UW MRSEC and have been incorporated into the web-based lab manual which was developed concomitantly with this course.

On "Micro" vs. "Nano"

When planning the course, the relative emphasis to place on micro- *vs.* nano-scale concepts was carefully considered. While a course devoted entirely to nano-scale concepts would have been feasible, it was decided that micro-scale topics should be included as well for several reasons. First, there was a lack of courses in micro-scale mechanics, and it was desirable to fill this gap considering the real and growing market in MEMS, for example. Furthermore, while there are many distinct scientific principles at play between the micro- and nano-scales, a number of micro-scale topics provide a useful bridge to nanoscale concepts. The example of MEMS is ideal here, since already at the microscale, surface effects like adhesion, which can be ignored at the macro-scale, have a decisive effect on the technology at the micro-scale. This naturally leads to a discussion of surface effects at the nanoscale that are relevant for NEMS, the proposed nano-scale analog to MEMS.

Laboratory Component

As mentioned above, the laboratory component of the course is comprised of several individual modules that are self-contained, yet build upon one another such that a final product is obtained by the end of the course. This final product is a microfluidic device for the filtration of an aqueous suspension of gold nanoparticles (Figure 2). In brief, the device utilizes a nylon membrane formed by an interfacial polycondensation reaction between two immiscible solutions, one containing adipoyl chloride and the other containing 1,6-hexanediamine. These solutions are brought into contact at an interface within a microfluidic device. The interface where this reaction occurs is stabilized by the surface treatment of the device substrate with hydrophilic and hydrophobic regions. The membrane forms at the "virtual wall" where these regions intersect and allows the device to be used as a filter capable of separating gold nanoparticles from an aqueous solution. The construction and testing of this device provides the students with an opportunity to investigate several nanotechnology and microfluidic phenomena during the course of the semester. Each major step in the construction of the device is devolved into a self-contained module which provides a hands-on tool for the teaching of nanoscale mechanics concepts.

a) b)

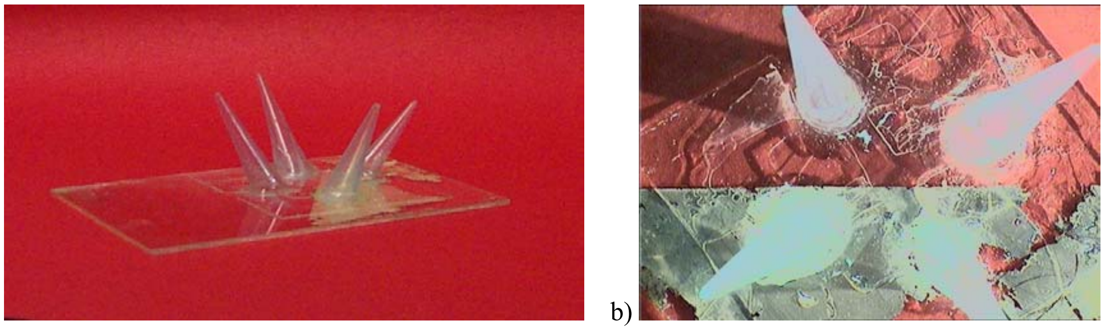

Figure 2. Side (a) and top (b) views of the microfluidic device constructed and tested during the course (before membrane formation). The surface modified silver coated portion of the substrate can be seen in the bottom half of image (b).

This lab was inspired by the research on "virtual walls" in microfluidic devices by Beebe and Moore[10,11] as well as the educational nanotechnology laboratories created by the University of Wisconsin Materials Research Science and Engineering Center (MRSEC).[12]

Module 1: Functionalization of a Silver Coated Substrate

The first module is designed to have the students examine the macroscopic properties of a surface before and after the surface is functionalized through adsorption of a monolayer of a substance which can modify the properties of that surface. Specifically, the students examine the contact angle of water on a silvered glass surface before and after the adsorption of an alkanethiol on the silver surface. Students begin with glass slides which have been pre-cleaned with piranha cleaning agent.

A portion of the glass slide is silvered utilizing a procedure adapted from a pre-existing UW MRSEC Nanoscale Video Lab Manual experiment (http://www.mrsec.wisc.edu/edetc/cineplex/Agthiol/index.html). After silvering the glass, the students then scrape off a portion of the silver layer with a razor blade and a straightedge to provide a sharp interface between the silvered and non-silvered portion of the glass slide. This interface will be utilized in a future module to stabilize the organic phase-aqueous phase interface during the production of the nylon membrane for the filtering of nanoparticles. Estimates of the contact angle of water droplets on the silver surface are then obtained utilizing a digitizing camera and microscope.

Functionalization of a portion of the silvered surface is carried out by the application of an alkanethiol solution to the silvered portion of the glass slide. The alkanethiol molecules form a self-assembled monolayer (SAM) on the silver surface with the alkane chain extending away from the surface as shown in Figure 3. The long alkyl chain of the alkanethiol in essence creates a new surface

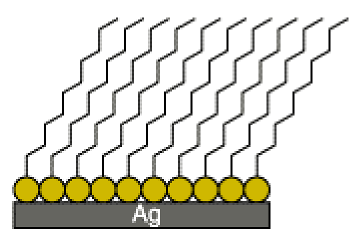

Figure 3. Schematic of alkanethiol SAM on silvered substrate

which is much more hydrophobic than the unfunctionalized silver surface. Once again, the contact angle of water droplets on the silvered surface is measured. This is then contrasted to the result obtained from the silvered surface prior to functionalization. This laboratory module is an effective tool for demonstrating that the modification of a surface on the nanoscale (*i.e.*, the adsorption of a monolayer) can have an impact on macroscopic properties such as the contact angle of water (Figure 4). Additionally, this module helps the students begin to focus on the role of surface properties in addition to bulk properties which have typically been emphasized in previous coursework the students have undertaken.

This module also serves as the first step in the construction of the microfluidic device by proving the initial substrate for subsequent construction steps. Functionalizing a portion of the substrate surface results in a hydrophobic region and a hydrophilic region on the surface of the substrate. The interface between these two regions provides a "virtual wall" to stabilize the interface for the two-phase nylon formation reaction.

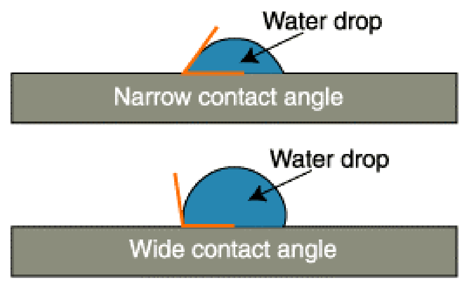

Figure 4. Schematic of contact angles of water on different surfaces.

Module 2: AFM Characterization of Surface Properties

The second module utilizes the functionalized and bare silver surfaces to explore the structure and mechanics of these surfaces utilizing the atomic force microscope (AFM). Self-assembled monolayers (SAM), because of their chemically inert functionalization, generally possess lower friction and adhesion than bare metal surfaces.[13] By taking adhesion and friction measurements on both the SAM-coated and bare portions of the silver-coated slide, these differences can be revealed both qualitatively and quantitatively. This experiment directly connects the observation of macroscopic phenomena (*i.e.*, contact angles) undertaken in the first module with nanoscale interfacial properties (adhesion) as measured by AFM.

Another goal of this module is to expose the students to hands-on AFM measurements. As the use of AFM techniques to image surfaces at and examine mechanical properties at the nano-scale becomes more prevalent in science and industry, it is important to ensure that students have hands-on experience in these techniques.

Module 3: Construction of a Microfluidic Device

The third module involves the construction of the microfluidic device to be tested in subsequent modules. The device is constructed by arranging four glass cover slips on top of the surface modified substrate to form two intersecting channels as illustrated in Figure 5. The intersection of these two channels is positioned on the substrate so as to ensure that the interface between the bare substrate and the functionalized silver layer runs diagonally through the intersection of the channels. A fifth glass cover slip is placed over top of the intersection of these channels to provide a "roof" for the channels. Plastic pipette tips are affixed with epoxy onto the coverslips such that the pipette tips act as conduits for the introduction of fluids into the microchannels of the device.

Once the channels have been constructed and the pipette tips secured to the inlets and outlets of the channels, a nylon membrane is formed utilizing a conventional two-phase reaction between a reactant in an aqueous phase (1,6-hexanediamine) and a reactant in an organic phase (adipoyl chloride). The reactants are introduced into the two channels at right angles to each other. The aqueous-organic interface formed at the intersection of the two channels is stabilized by the presence of a virtual wall for the aqueous phase at the boundary of the bare glass substrate and the functionalized silver coating. The interfacial polycondensation reaction is allowed to occur for 5 to 10 minutes to form a nylon membrane at the boundary between the bare glass and the functionalized silver coating, and then the channels are rinsed with appropriate solvents to remove any unused reactants from the channels.

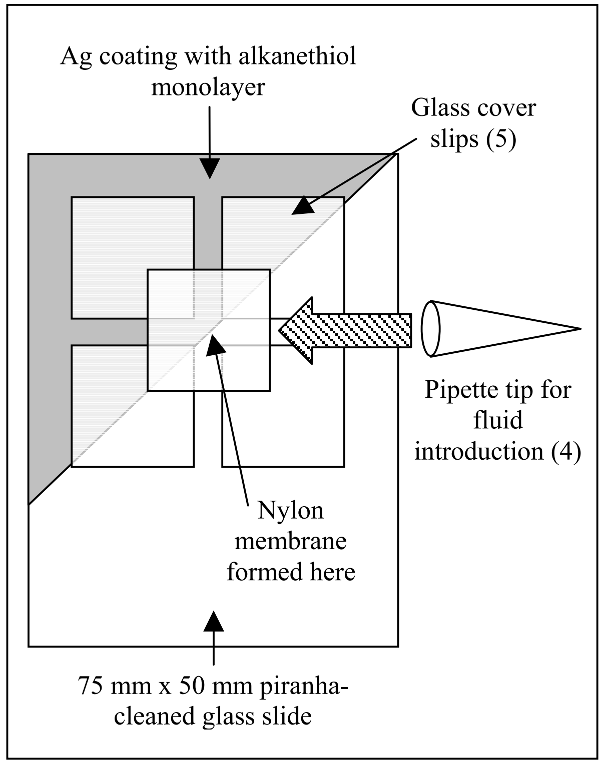

Figure 5. Schematic of microfluidic nanoparticle filter constructed in module 3 of the laboratory.

Students are encouraged to make several surface-modified substrates in Module 1 so that they are more likely to be able to produce a functioning device in Module 3. Practice is required to successfully construct the channels and apply the pipette tips. Students are also encouraged to vary the nylon reaction time in order to produce several devices with varying membrane thicknesses.

Module 4: Synthesis of Collodial Gold Nanoparticles

The fourth module involves the students synthesizing nanoparticles of gold in an aqueous colloidal suspension. This experiment is also adapted from the MRSEC website (http://www.mrsec.wisc.edu/edetc/cineplex/gold/index.html). This involves the reduction of a gold complex ($AuCl_4^{2-}$) by sodium citrate. The reduction reaction proceeds fairly slowly and nanoparticles of gold are formed over the course of about one hour resulting in a colloidal suspension which has a deep-red color as shown in Figure 6.

Figure 6. Photograph of a colloidal suspension of Au nanoparticles in water.

This straightforward lab experiment provides the students with an opportunity to experience hands-on synthesis of a nanostructured material as well as provides nanoparticles with which the microfluidic filter can be tested.

Module 5: Testing of the Microfluidic Nanofilter Device

The fifth module is the testing of the filtering capabilities of the microfluidic filter as measured by the students. The colloidal gold produced in the fourth module is utilized as the solution to be filtered and is filtered with the microfluidic device constructed in the third module. Figure 7 shows the change in the colloidal solution from red to nearly clear after filtration. The particles filtered from the solution by the device are recaptured and saved for analysis in the final module.

Figure 7. Colloidal gold solution before (left) and after (right) filtration through the microfluidic device.

The final module returns to AFM techniques to once again expose the students to the use of an AFM. In this module, the filtered particles are characterized with the AFM. Students can then judge the efficacy of their microfluidic filter in a semi-quantitative manner.

Conclusions

Although many courses around the country have been introduced either based on nanotechnology or incorporating nanotechnology, this course represents the first course (to our knowledge) to be offered in the area of *engineering mechanics*. The number of nanotechnology courses in different disciplines is demonstrative of the interdisciplinary nature of nanotechnology. This need for interdisciplinary approaches to nanotechnology is evident in this course which focuses on the mechanics aspects of micro- and nano-scale systems, but also incorporates concepts from other disciplines, most prevalently, chemistry and materials science.

This course combines traditional pedagogy with immersive and reflective components to provide a broad and deep understanding of the course material and its current and potential application to the students involved in the course. In particular, the laboratory component of the course provides a hands-on experience with synthesis techniques, nanoscale materials characterization, and microfluidics. This multi-faceted approach to the instruction of this subject material has proven to be an effective as well as engaging manner in which to engage students in learning about micro- and nanoscale mechanics.

Acknowledgements

We are grateful to the National Science Foundation though the Materials Research Science and Engineering Center (MRSEC) on Nanostrcutured Materials and Interfaces (award # DMR-0079983) and CAREER Awards to Wendy Crone (award # CMS-0134385) and Robert Carpick (award # CMS-0134571) for supporting the development of our curricular materials and their implementation. We would also like to thank the research groups of D.J. Beebe at the University of Wisconsin - Madison and J.S. Moore at the University of Illinois – Champaign/Urbana for their assistance in the early stages of the laboratory development.

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Robert W. Carpick is an assistant professor in the Engineering Physics Department, University of Wisconsin-Madison. He teaches in the Engineering Mechanics and Astronautics program. His research focuses on the study of friction and mechanics at the nanometer scale. Prof. Carpick is interested in applying innovative learning techniques in the classroom, and in expanding the engineering curriculum to include topics in nanoscience and nanotechnology.

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Kenneth W. Lux is a post-doctoral research associate at the University of Wisconsin – Madison (BS and MS in Chemical Engineering, Case Western Reserve University; PhD. In Chemical Engineering, University of California at Berkeley) working on the development of new course material for nanotechnology education in engineering.

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Buck D. Johnson received his B.S. degree in mechanical engineering from the Illinois Institute of Technology in 2000 and his M.S. in biomedical engineering from the University of Wisconsin – Madison in 2002. His research includes work in the mechanical characterization of responsive hydrogels used in microfluidic devices.