# Incorporating Nanotechnology into Undergraduate Education

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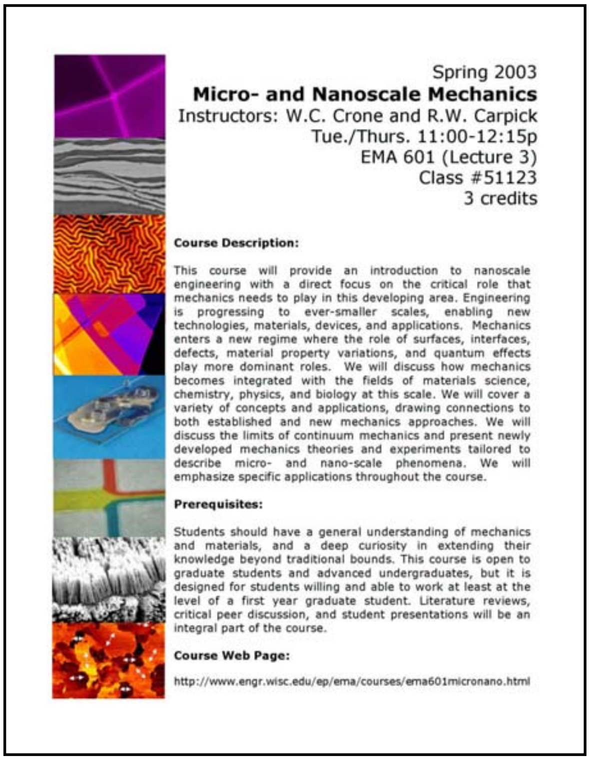
## ABSTRACT

A new course in nanoscale mechanics for engineering students was recently taught at the University of Wisconsin - Madison. Mechanics enters a new regime at the nanoscale, where the effects of surfaces, interfaces, defects, material property variations, and quantum effects are accentuated. 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 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, a hands-on laboratory utilizing the atomic force microscope, and a laboratory construction of a nanofilter devices using microfluidic technology.

## 1 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 exceptionally broad impact [2].

The importance of this emerging technology to society and industry requires that colleges and universities 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].



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.

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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 [7-9]. In addition, courses in nanotechnology have begun to appear in college catalogs, and nanotechnology concepts have been incorporated into undergraduate general chemistry, physics and engineering courses [4]. Additionally, during the same semester that the course on nano-scale mechanics described below was introduced at the University of Wisconsin – Madison, mechanics courses were also introduced at Northwestern University and Massachusetts Institute of Technology.

This paper describes a new mechanics-oriented nanotechnology course in the Department of Engineering Physics (Figure 1). This course, entitled, "Micro- and Nanoscale Mechanics," is designed to introduce undergraduate and graduate 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, were combined with reflective writing assignments and the submission of a nanotechnology review manuscript to a simulated peer-reviewed journal edited by the instructors and other students in the course.

## 2 COURSE DESCRIPTION

The content of the "Micro- and Nanoscale Mechanics" 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 material on 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, including surface characterization and surface forces, particularly as applied to scanning probe microscopy (SPM) and micromachines (MEMS), experimental material characterization techniques at the micro- and nansocale, theoretical and computational techniques for modeling nanoscale systems, and the applicability of traditional macroscale mechanics concepts to nanoscale systems.

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 microelectromechanical systems (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 anaolog to MEMS.

In addition to the classroom activities, which include traditional lectures as well as demonstrations and small-group activities, there was a significant laboratory component designed to accompany this 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 complement the subject matter under discussion in the course. Video-based lab procedures have been developed for these modules through the UW MRSEC and have been incorporated into the web-based *Laboratory Manual for Nanoscale Science and Technology* available at http://www.mrsec.wisc.edu/nano/.

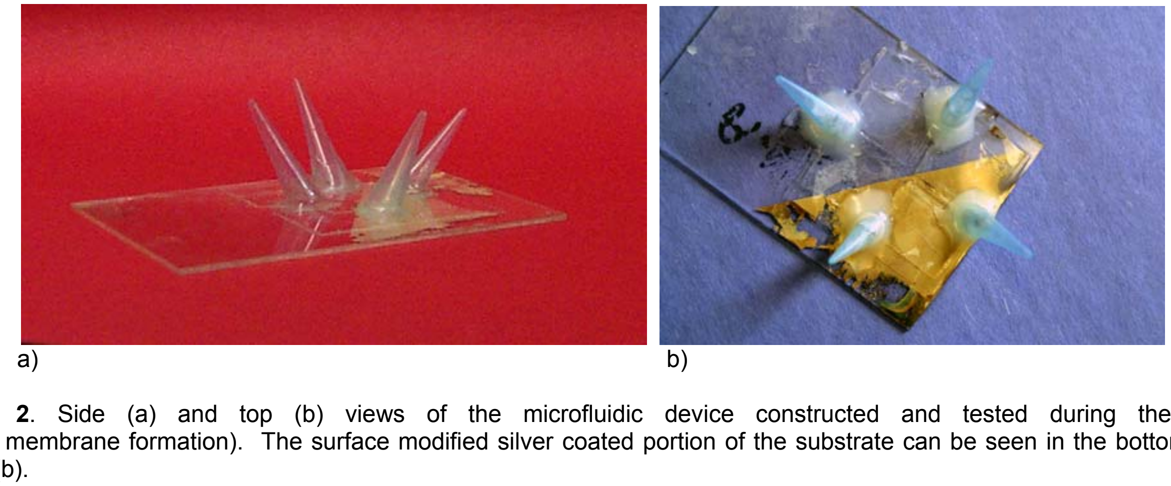
a) b)

**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).

## 3 LABORATORY COMPONENTS

As mentioned above, the laboratory component of the course was 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 provided 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 was devolved into a self-contained module which provides a hands-on tool for the teaching of nanoscale mechanics concepts.

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 was 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 modifies 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 *Laboratory Manual for Nanoscale Science and Technology* 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 (Figure 3a). This interface is 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.

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. The long alkyl chain of the alkanethiol in essence creates a new surface which is much more hydrophobic than the unfunctionalized silver surface. The change from a hydrophilic to a hydrophobic surface behavior can be easily observed as Figures 3b and 3c illustrate. The contact angle of water droplets on the silvered surface before and after functionalization can also be quantified utilizing a digitizing camera and microscope.

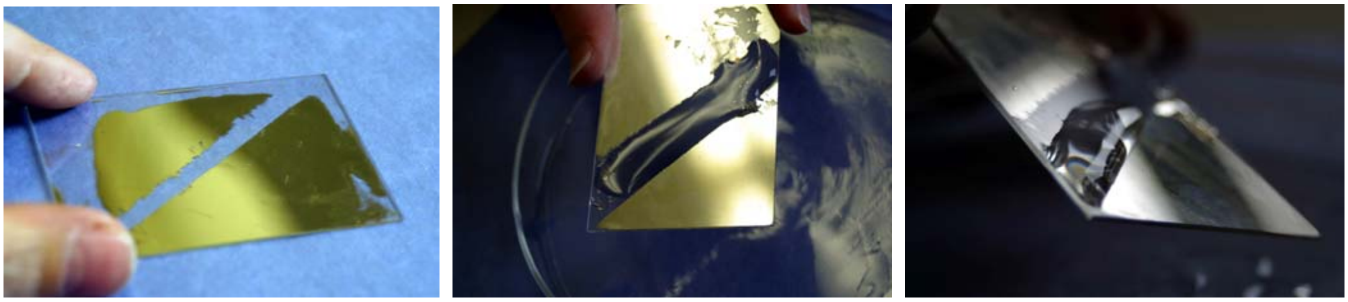
a) b) c)

**Figure 3**. The substrate shown in (a) contains a region where the silvering has been removed (center) to provide a sharp interface next to a silvered region functionalized with alkanethiol molecules (right). When water is placed on the bare surface of the slide and brought to the interface as in (b), the hydrophobic nature of the functionalized silver region can be easily observed. The water is repelled from the functionalized sliver by the self assembled monolayer even after tilting the slide to a severe angle as shown in (c).

This first 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, it helps the students begin to focus on the role of surface properties in microscale and nanoscale device in addition to bulk properties which are typically emphasized in traditional engineering coursework. This module also serves as the first step in the construction of the microfluidic device by providing the initial substrate for subsequent construction steps. The interface between the hydrophobic and hydrophilic regions allows the creation of a "virtual wall" where a two-phase nylon formation reaction can be conducted.

### *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. It also revealed challenges and limitations at the nanoscale, such as the significance of surface contamination and the presence of roughness at scales below that which is visible.

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.

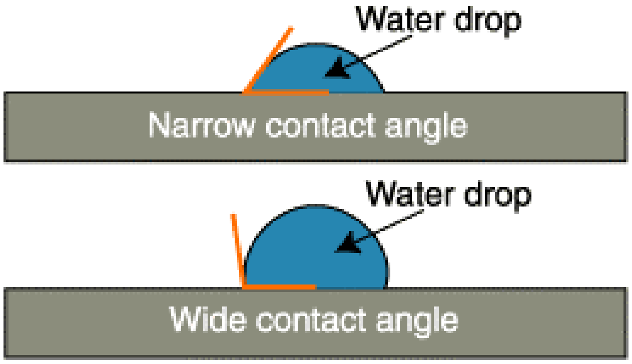

**Figure 4**. Schematic of contact angles of water on different surfaces.

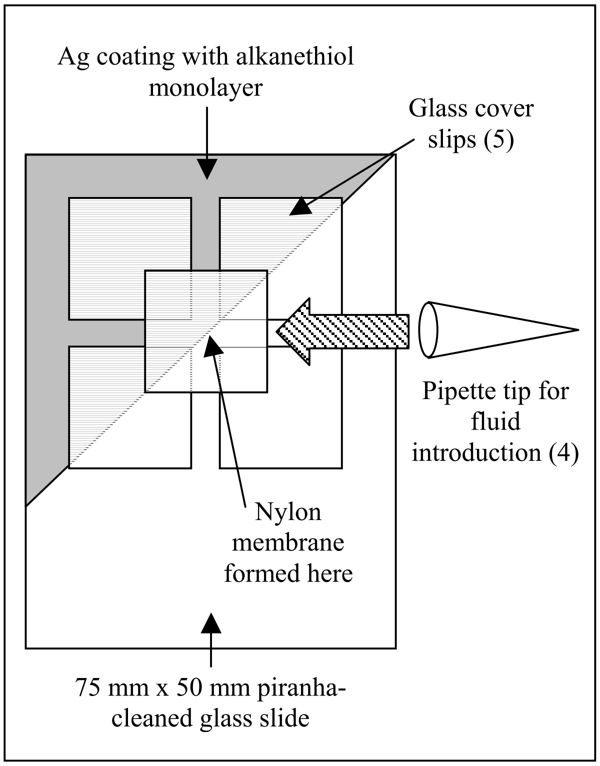

**Figure 5**. Schematic of microfluidic nanoparticle filter constructed in module 3 of the laboratory.

Practice is required to successfully construct the channels and apply the pipette tips. 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. 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 ($AuCl_4^{1-}$) 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.

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.

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

### *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 remnant color observed in the filtered solution is a result of the smallest nanoparticles passing through the filter membrane. The particles filtered from the solution by the device are recaptured and saved for analysis in the final module.

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 then judged the efficacy of their microfluidic filter in a semi-quantitative manner by imaging the nanoparticles after transfer to a substrate.

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

## 4 CONCLUSIONS

Although many courses around the country have been introduced either based on nanotechnology or incorporating nanotechnology, this course is among the first to be offered in the area of *engineering mechanics*. While this course focuses on the mechanics aspects of micro- and nano-scale systems, it also stresses the interdisciplinary nature of nanotechnology by incorporating 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

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