AC 2011-224: NUE (EEC): INTEGRATING NANODEVICE DESIGN, FABRICATION, AND ANALYSIS INTO THE MECHANICAL ENGINEERING CURRICULUM

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Santosh Devasia is the Principal Investigator of a recently funded grant from the NSF Nanotechnology Undergraduate Education (NUE) Program, Grant # EEC 1042061; the proposed educational efforts under this NUE grant are described in this paper.

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Jae-Hyun Chung is McMinn Endowed Assistant Professor in the Department of Mechanical Engineering at University of Washington. Dr. Chung received his B.S. in 1995 and M.S. in 1997 from Sungkyunkwan University in Korea. His Ph.D was earned in 2004 from Northwestern University in the field of electric field guided assembly of carbon nanotubes. He has received awards including, the McMinn Endowed Professorship, an NSF Career Award, and a Bill and Melinda Gates Foundation Award.

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Amy Shen, University of Washington

Professor Amy Shen is an Associate Professor at Mechanical Engineering department from University of Washington. She earned her Ph.D in Theoretical and Applied Mechanics from the University of Illinois at Urbana-Champaign. She was a postdoctoral research fellow at Harvard University and an assistant professor at Washington University in St. Louis from 2002-2007.

Amy Shen's research program concerns complex fluids and the processing of these fascinating materials to create morphologies and structures that can find application in the nanotechnology, biotechnology, and energy related materials. Within this broad area, her laboratory takes advantage of the coupling of complex fluid microstructures with the spatial confinement that is possible by using microfluidic flow methods, to offer exquisite morphological control of soft materials.

Nathan Sniadecki, University of Washington
Junlan Wang, University of Washington

Junlan Wang has been an Associate Professor in the Department of Mechanical Engineering at the University of Washington since Dec. 2008. Before joining UW, she was an Assistant (2003-2008) and then Associate Professor (2008) in the Department of Mechanical Engineering at the University of California, Riverside.

Professor Wang's research is in the area of nano and micromechanics of complex material systems. She is interested in developing novel experimental techniques complemented by numerical and analytical approaches to study the mechanics and physics of materials and structures at small spatial and temporal scales.

Professor Wang is a member of ASEE, ASME, MRS and SEM.

Integrating Nanodevice Design, Fabrication, and Analysis into the Mechanical Engineering Curriculum

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I. Introduction

This article describes a new nanotechnology undergraduate education (NUE) program on the design of nanodevices in the Mechanical Engineering Department at the University of Washington. The goal of the NUE program is to prepare mechanical engineers to design nanodevices. The NUE program leverages existing strengths of the Mechanical Engineering (ME) curriculum in analysis, fabrication, and design of (larger-scale) devices by integrating novel developments and unique challenges in nanodevices into the ME curriculum.

It is noted that educational efforts in nanodevices have become important as nanotechnologies move from research laboratories into industries. For example, nanodevices are critical to renewable energy and next-generation electronics. Additionally, nanodevices have applications in biotechnologies, e.g., in the development of sensors for early detection and prevention of disease. The proposed NUE program will integrate issues in the engineering of nanodevices into the undergraduate curriculum to prepare the engineering workforce for emerging nanotechnology industries.

Traditional mechanical engineering (ME) curriculum covers issues in analysis, fabrication, and design of (larger-scale) devices. Therefore, to prepare engineers to work on nanodevices, the proposed modules will integrate the novel developments and unique challenges in nanodevices into the ME curriculum. The specific nanodevices covered in the modules will include: nanogels for biomedical applications; nanofiber composites for solar cells, batteries and thermoelectric modules; nanodevices for bio/chemical sensors and a nanotip enrichment system; novel nanosteppers for nanopositioning systems; nanoposts for nanoscale biological studies; and nanoscale thin films testers.

The learning outcomes of this program are that students who participate in the proposed program should be able to: (i) analyze nanodevices using appropriate theoretical and experimental approaches; (ii) explain basic elements of fabrication processes for nanodevices; and (iii) solve open-ended, nanodevice-design problems. Examples of the nanodevices covered in the eight courses (affected by the proposed modules), and their relation to the three learning outcomes are outlined in Figure 1.

The article describes the theoretical and experimental modules in nanodevices developed for this new NUE program. These modules are systematically and sequentially linked and integrated with eight courses that currently exist in the ME curriculum at the University of Washington (UW). Five of these courses are core required ME courses (at the UW) that are offered in typical ME curriculum at other universities. This integration into existing core ME curriculum will facilitate the potential adoption of the proposed nanodevice modules at other universities, and thereby, benefit the ongoing efforts to develop nanotechnology curriculum for undergraduate education.

Level	Course and Lead Faculty	Specific Nanodevice(s) in Proposed Modules	Outcomes (Analysis/Fabrication/Design) and Novel Concepts
Junior level	**Course:** ME 333 **Title:** Intro to Fluid Mechanics **Prof.** Amy Shen	Nanogels	**Analysis:** Wettability; complex fluids and effect on nanostructures **Fabrication:** Self assembly, scalability, microchannels for nanofabrication **Design:** nanoposts, optimization, and bio-applications
Junior level	**Course:** ME 354 **Title:** Mechanics of Materials Laboratory **Prof.** Jiangyu Li	Nanofiber composites	**Analysis:** Experimental nano-surface characterization (profiling and indentation) using an atomic force microscope. **Fabrication:** Laboratory modue for nano structured surfaces
Junior level	**Course:** ME 356 **Title:** Machine Design Analysis **Prof.** J. Chung	Nano bio/chemical sensors	**Fabrication:** High-throughput molecular-level assembly and fabrication of example nanodevices
Senior level	**Course:** ME 440 **Title:** Advanced Mechanics of Materials **Prof.** Jiangyu Li	Nanoindenter	**Analysis:** Nanomechanics and its application in the design and analysis of nanofabrication and nano-characterization
Senior level	**Course:** ME 471 **Title:** Automatic Controls **Prof.** S. Devasia	Nanosteppers	**Analysis:** Modeling and control of piezo actuators used in nanopositioning systems **Design:** Novel devices to overcome bandwidth and range tradeoffs in nanopositioning systems
Senior level	**Course:** ME 498 **Title:** Nanodevice Design and Manufacture **Prof.** J. Chung	Nanotip enrichment device	**Analysis:** Deterministic and probabilistic forces **Fabrication:** Carbon-nanotube assembly on interdigitated electrodes; automated assembly of individual nanowires **Design:** Nanotip enrichment device for biosensors; tuberculosis and cancer detection
Senior level	**Course:** ME 498 **Title:** Bio-Framework for Engineers **Prof.** N. Sniadecki	Nanopost-based bio-sensors for cell mechanics	**Analysis:** Mechanics of nanoposts **Fabrication:** Nanopost fabrication **Design:** Optimization of post geometry, and cell-material interactions
Senior level	**Course:** ME 499 **Title:** Mechanics of Thin Films **Prof.** J. Wang	Nanoscale thin film tester	**Analysis:** Adhesion, delamination, fracture **Fabrication:** Thin film tensile tester **Design:** Nanoscale thin film tester
Senior level	**Course:** ME 495 **Title:** Capstone Design **Prof.** All Investigators	Nanodevice projects	**Design:** Research-type open-ended projects will be offered on nanodevice design

Fig. 1. Relation between novel concepts in nanodevices in proposed modules and the learning outcomes in the eight courses impacted by the proposed NUE program. Recently developed courses are initially assigned the numbers ME 498 or ME 499 before a permanent unique number is assigned. The other five courses (ME 333, ME 354, ME 356, ME 440, ME 471, and ME 495) are core Mechanical Engineering (ME) courses that are found in typical ME undergraduate programs.

II. Pedagogical Issues

The objectives of the NUE program are to develop important aspects of the student's knowledge about nanodevices: factual; conceptual; procedural and meta-cognitive as in modern taxonomy of learning objectives [1]. The learning objectives for the proposed modules will target cognitive processes such as remembering (developing a knowledge base of factual and procedural information), understanding (linking knowledge in a more comprehensive conceptual framework) and applying (related to fabrication and analysis), as well as analyzing, evaluating and creating (related to design aspects of nanodevices) and promoting higher levels of learning. In addition to design opportunities spread throughout the different modules, the students will participate in open-ended, research-type projects, which will allow students to explore novel and creative aspects of nanodevice design. The relations between the taxonomy of nanodevice-knowledge objectives in the different courses affected by the proposed NUE project are shown in Figure 2.

	Course and Lead Faculty	Factual Knowledge	Conceptual Knowledge	Procedural Knowledge	Meta Cognitive Knowledge
Junior level	ME 333: Intro to Fluid Mechanics **Prof.** Amy Shen	X	X		X
	ME 354: Mechanics of Materials Laboratory **Prof.** Jiangyu Li	X	X	X	
	ME 356: Machine Design Analysis **Prof.** J. Chung	X	X	X	
Senior level	ME 440: Advanced Mechanics of Materials **Prof.** Jiangyu Li	X	X	X	
	ME 471: Automatic Controls **Prof.** S. Devasia	X	X		X
	ME 498: Nanodevice Design and Manufacture **Prof.** J. Chung	X	X	X	X
	ME 498: Bio-Framework for Engineers **Prof.** N. Sniadecki	X	X	X	X
	ME 499: Mechanics of Thin Films **Prof.** J. Wang	X	X	X	X
	ME 495: Capstone Design All Investigators		X	X	X

Fig. 2. *Different types of nanodevice knowledge (based on the taxonomy of educational objectives [1]) that are targeted by the modules developed under the proposed NUE program.*

III. Details of Planned Modules

Details of the modules developed for the eight courses (in Fig. 1) are provided in this section.

A. ME333 Intro to Fluid Mechanics; Lead: Prof. A. Shen

1) Overview: Fluid mechanics investigates the flow of liquids and gases. This Junior-level course focuses on the fundamental principles to describe fluids at rest and in motion. The conservation of mass, momentum, and energy (governing equations), Navier-Stokes equation are introduced and dimensional analysis is also discussed. Teaching fluid mechanics to undergraduates can be a challenging task. Prof. Shen has been incorporating hands on experiments and demos during class (such as soap film experiments to illustrate the concept of surface tension) to motivate students for critical thinking. Cultivation of such abilities will help them perform better in process/product design tasks in the future. The *microfluidics enabled nanogel module* proposed here will be integrated into the sections of *Flow in pipes and Dimensional Analysis* in our original curriculum. This module will serve the need for mechanical engineering students to be exposed to nanotechnology and illustrate how the traditional fluid mechanics operating parameters can manipulate nanogel synthesis. This module is in line with Dr. Shen's current research on complex fluids under confinement. The outcomes impacted by this module are: (i) analysis (pressure drop in pipe flows and scaling analysis); (ii) fabrication of nanogels; and (iii) design and testing of microfluidics device for nanogel synthesis.

2) The Microfluidics Enabled Nanogel Module: Nanoporous gels and scaffolds hold an enormous potential in improving the performance of biosensors as porous scaffolds can serve as excellent encapsulating matrix to various bioagents [2], [3]. The proposed module will use the knowledge base gained recently by Dr. Shen's group on synthesizing biocompatible and stable nanoporous scaffolds with the proper hydrodynamic conditions for a given self-assembly precursor [4]. When subject to flow, flow induced structure formations of micelles (found in soap and detergent) occur in a narrow range of concentrations of specific ionic surfactant solutions with added salts and can be used as nano-templates [5]. However, the major challenge of utilizing self assembled structures as nano-templates is the structure breakdown and the disintegration once the flow is stopped. Dr. Shen's group is able to obtain *irreversible* nanoporous scaffolds by using specially designed microfluidic devices (see Fig. 3, [4]). The irreversible gel formation results from the large shear and extension strain rates and total strain generated by the flow through the device, under a mixed extensional and shear flow conditions.

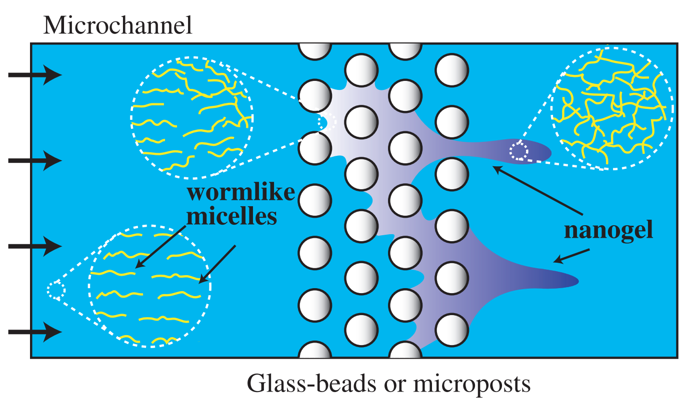

Fig. 3. Design of the nanogel fabrication. Micron size particles are introduced inside microchannels to achieve high shear and extension rates that leads to the generation of nanogels. The flow parameters can be designed to tailor the nanogel properties.

The proposed module will focus on the nanogel formation criteria by varying microfluidic design and flow conditions. The module will illustrate how the traditional fluid mechanics operating parameters (i.e. flow rates in a pipe, pressure drop, and pipe wall properties) can enable the nanogel formation under a microfluidic environment. In particular, this module shows how to construct nano-structures with functional features spanning molecular to macroscopic length scales in a fluidic environment.

3) Analysis of Microfluidics Enabled Nanogel synthesis: Students will learn the principle of pressure drop and velocity profile of fluids flowing inside a pipe from the traditional fluid mechanics curriculum. Here, we will ask students to compare their analysis results between macro- and micro-scaled pipes. With micro-scaled pipes, the boundary conditions will be modified. Based on their velocity profile calculation, students will be asked to estimate the shear rate and extension rate in the microfluidic channel with given flow rates. Based on the rheological and hydrodynamics calculations, students will determine the minimum flow rate requirement to obtain nanogels.

4) Fabrication of nanogels and microfluidics devices: The creative usage of microfluidics to access the high shear and extension rates needed to form nanostructured scaffolds is the focus of the fabrication part of this module. The goal is to develop simple and robust microdevice fabrication procedures to familiarize students with soft lithography techniques as routinely practiced in Dr. Shen's lab. Once the microdevice is fabricated, students will pump the surfactant based solution (water alike) through the microchannel with randomly packed particles. Under proper flow rates, permanent nanogels can be formed, and be visualized (almost like a hair gel product). Through this fabrication laboratory exercise, students will be able to understand the relationship between hydrodynamics parameters and the nanogel formation criteria.

5) Design and Testing of nanogels: We will incorporate this part with the dimensional analysis section of the curriculum. After introducing dimensional analysis, we will encourage students to propose what are the key dimensionless numbers (i.e. Reynolds number, Peclet number and important length scale ratios) involved with the nanogel/microfluidics problem. Students will be asked to identify the design principles (based on their nanogel fabrication results). Through this exercise, students will learn how to tune the morphology of flow induced nanoporous scaffolds by varying the microchannel width and depth, and flow conditions. Students will also be asked to increase the nanogel production by novel parallel design as a bonus project. For guided nanomaterials synthesis at high rates and over large areas, we require a good understanding of the interfacial behavior and forces required to assemble, detach, and transfer nano-components. Students will learn the challenging issues on how to successfully transfer knowledge from the lab into real technology.

B. ME354 Mechanics of Materials Laboratory; Lead: Prof. J. Li

1) Overview: This junior level course provides undergraduate engineering students hand-on applications of fundamental concepts in mechanics of materials, structures, and systems that are important to Mechanical, Materials, Civil and Aerospace Engineering. Mechanics of materials fundamentals are taught during lecture sessions, and then practiced, demonstrated, and verified by students during laboratory sessions. Traditional topics are covered, including (1) stress and strain analysis and constitutive behavior of materials; (2) tension, torsion, bending, indentation, impact, and buckling testing of structures; and (3) plasticity, fracture, fatigue, and creep of materials. No topics related to nanotechnology are included in this course at the moment, such topics will be developed under the proposed module.

2) The Nanofibers Module: In the Multifunctional Materials Laboratory at the Univ. of Washington, Dr. Li is developing composite nanofibers with hierarchical porous structures for dye sensitized solar cells, and similar nanocomposite structures for Li ion batteries and thermoelectric modules, see Fig. 4. Mechanical reliability is extremely important for those nanodevices, and therefore reliability (bending-based) testing of functional nanofibers under the atomic force microscopic will be included in the proposed lab module. Additionally, nanofiber specimens will be fabricated and added to the existing tensile testing lab, and the impact testing lab.

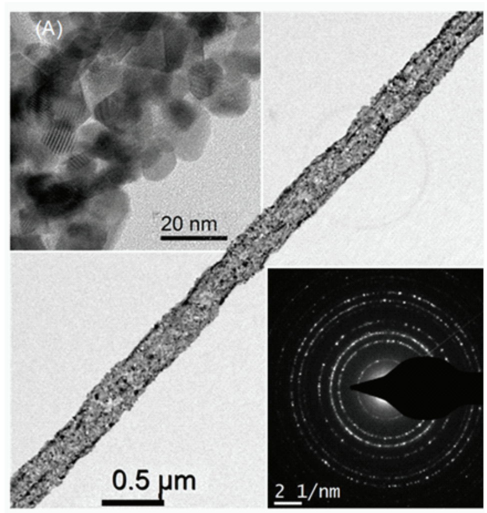

Fig. 4. Nanocrystalline thermoelectric oxide nanofiber synthesized in Dr. Li's Multifunctional Materials Laboratory for high efficiency thermoelectric energy conversion.

3) Fabrication: In this lab, clay reinforced and carbon nanotubes reinforced Nylon6 nanocomposites will be processed at Multifunctional Materials Laboratory at UW. We are equipped with HAAKE Minilab Micro-compounder for melt based polymeric nanocomposite processing (see Facilities). As a conical double-screw extruder with a back flow channel, it can be operated as a circulation reactor, and thus uses the advantages of both extruder and mixer. Both co-rotating and counter-rotating pairs of screws can be used, and either rotation speed or torque can be controlled. Nylon6 polymer and nanofillers will be mixed using this Micro-compounder, and specimen for tensile testing and impact testing will be fabricated. Functional composite nanofibers will also be synthesized by electrospinning for bending testing.

4) Analysis: Currently, both polymers and metals are tested in our undergraduate laboratory during bending lab, tensile testing lab and impact testing lab, and for each lab, we will add nanocomposite specimens as well, so that students can compare the difference in stress-strain curves, tensile modulus, strength, ductility and impact toughness among different materials, and appreciate the superior mechanical properties of nanocomposites. In particular, Nylon6 with and without nanofillers embedded in will be compared, and both the enhancement and possible degradation in mechanical properties of nanocomposites will be demonstrated. The labs will be complemented by lectures, where we will have in-depth discussion on the deformation mechanism of nanocomposite materials, the effects of size and interface on the overall behavior of the nanocomposites, the potential property enhancement and possible degradation, as well as new design consideration associated with nanocomposites in connection with their civil, mechanical, and aerospace applications. An enhancement in one set of properties of nanocomposites is often accompanied by degradation in others, and it is important to emphasize a balanced point of view, so that students can make appropriate trade-off in future design and analysis of structures and systems involving nanocomposites. These theoretical analyses will complement what students learned in the lab, and give students a solid understanding on mechanics of nanoscale materials, devices, and systems.

C. ME356 Machine Design Analysis; Lead: Prof. J. Chung

1) Overview: The current junior-level Machine Design and Analysis course focuses on the design and analysis aspect of macroscale mechanical components along with the associated manufacturing processes. A module is proposed to introduce the major challenges and innovations (such as dominant forces at the nanoscale, and directed assembly) in the fabrication of nanodevices into this course. The outcome impacted by this module is the fabrication of nanodevices.

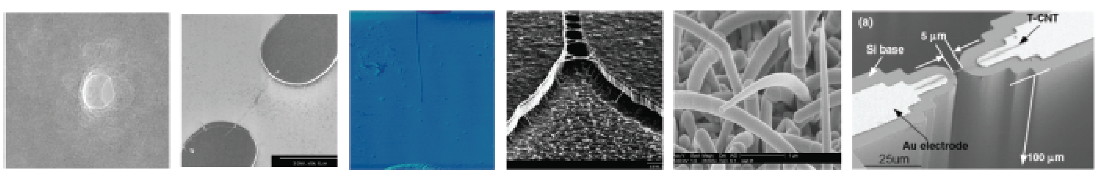

Fig. 5. Examples of Dr. Chung's research on nanodevices that will be covered in the proposed module (from left to right): nanoporous biosensor [6]; carbon nanotube device [7]; DNA sensor [8]; nanotube chemical sensor [9]; Si nanowire sensor; and a nanomaterial tester [10].

2) Fabrication: The Nanodevice Bio/Chemical Sensors Module: Fabrication procedures for example nanodevices will be introduced in this module. The need for such small scale devices will be discussed. The lecture will also discuss manufacturing and design challenges in the assembling of nanomaterials in an addressable way. Exemplary devices from Dr. Chungs previous work (see Fig. 5)) will be introduced along with the fabrication steps, which will prepare undergraduate students for future nanodevice design. The nanodevices covered in the class will include the following (which are a focus of Dr. Chung's research): a nanoporous biosensor [6]; integration of carbon nanotube devices [7]; a DNA sensor [8]; nanotube chemical sensors [9]; Si nanowire sensors; a nanomaterial tester [10]; a chemical response sensor [11]; and nanoelectrodes for virus detection developed in collaboration with Dr. Liu at Northwestern University [12] . The major focus will be to deliver the concept of fabrication and manufacture for nanodevices, and the differences between fabrication of nanodevices as opposed to larger devices that ME students are accustomed to. For example, we will discuss that most nanoscale components are assembled in solution phase, while macroscale devices are machined in dry conditions. The effect of these different conditions will be discussed. Additionally, the requirements and challenges for modeling and simulation will be discussed along with a study of dominant forces at work at the nanoscale. Homework problems will be assigned to review the fabrication steps for a device of interest and to identify the challenges in its fabrication.

D. ME440 Advanced Mechanics of Materials; Lead: Prof. J. Li

1) Overview: This senior level course covers advanced mechanics of materials, structures, and systems. Currently it only focuses on conventional mechanics topics, and does not touch nanoscale analysis and theory. We propose to further explore nanodevice topics that we plan to introduce in the earlier ME 354 course. In particular, we will introduce nanoscale contact mechanics into the curriculum, which is relevant to atomic force microscopy and nanoindentation. These new topics will be implemented in the spring quarter of 2011 and beyond. (To make room for these new topics, review of basic subjects covered in ME 354 at the beginning of ME 440 will be shortened, and some of the conventional topics will be consolidated.)

2) The Nanoindenter Module: Indentation test is one of the most commonly used methods to probe the nanoscale mechanical properties. It presses a hard round ball or point against the material sample, and measure the depression or indentation resulted from plastic deformation beneath the indenter, from which the hardness of the materials and other related mechanical properties can be determined. Due to the relative large size of the indenter, the conventional indentation tests are not adequate for testing materials of small size, or materials with small heterogeneity, such as nanocomposites. Nanoindentation was developed for this purpose, where small load and tip size are used, so that the indentation area may only be a few square micrometers or even nanometers, making it ideal for testing nanoscale devices, and systems. Undergraduate students usually do not have access to nanoindentation in their study, which we seek to provide through this new module using our Asylum Research Nanoindentor available in Dr. Li's laboratory. In particular, we will add an experimental session for nanoindentation testing, so that the students can get hand-on experience with the state of art nanomechanical characterization technique.

3) Analysis: The load-displacement curve obtained from nanoindentation testing can be used to estimate the modulus of elasticity, hardness, strain rate sensitivity, and activation volume. As a result, nanoindentation has been increasingly used in research laboratories and industry to study nanoscale structures, thin films, nanocrystalline materials and nanocomposites. The interpretation of the data, however, critically depends on the contact analysis at nanoscale, while it is much more complicated than the conventional theory due to the small size involved. We will have in depth discussions on nanoindentation from contact mechanics point of view. The deformation mechanism of small size structure, the new phenomena in nanoscale materials and systems, and data analysis of load-displacement curve will also be discussed in connection with nanoindentation experiments. Furthermore, term project based on nanoindentation will also be assigned. This will help students to correctly analyze nanoindentation data that are generally difficult to interpret.

E. ME471 Automatic Controls; Lead: Prof. S. Devasia

1) Overview: This senior-level course currently focuses on feedback control, such as typical proportional-integral-derivative (PID) control, of linear systems. A module is proposed on control of nanopositioning systems — the specific nano-system considered will be inchworm nanosteppers for use in scanning probe microscopes, which is the focus of Dr. Devasia's current research. The outcomes impacted by this module will include: (i) analysis (modeling and control) of piezo actuators used in nanopositioning systems; and (ii) the design of mechanisms used in nanopositioning systems.

2) The Inchworm Nanostepper Module: Nanopositioning systems are critical components of scanning probe microscopes (SPMs), which in turn, are key enabling tools in the investigation and manipulation of nano scale (and sub-nano scale) phenomena [13].

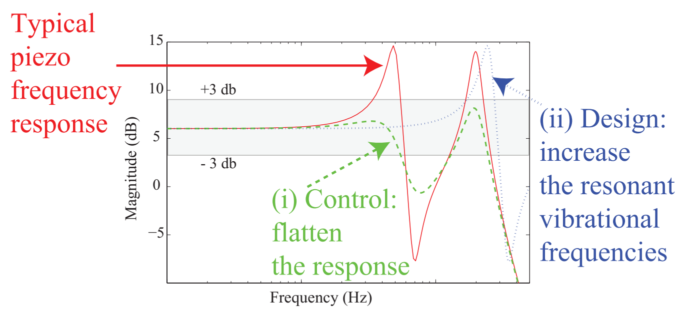

Fig. 6. Approaches to increase bandwidth of a piezo nanopositioner: (i) control approaches to flatten the frequency response; and (ii) design approaches to increase the smallest resonant-vibrational frequency, which limits bandwidth.

Recent research efforts have aimed to increase the range of the nanopositioning systems used in SPMs without loss of bandwidth (throughput), e.g., [14]-[16]. Note that large range is required, e.g., to generate nanopatterns over a large area along with the interconnections between nanofeatures in SPM-based nanofabrication methods, e.g., [17]. However, it is also important to maintain high-bandwidth in such SPM nanpositioining systems to ensure high throughput, which is critical for economic viability.

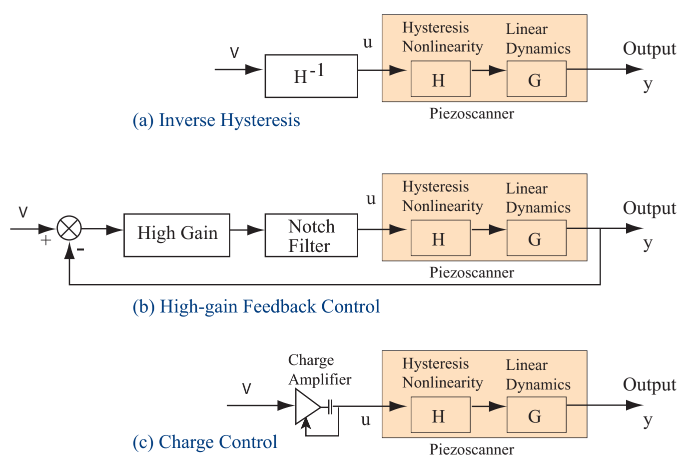

Fig. 7. *Three different approaches to linearize hysteresis nonlinearity in piezoscanners. (a) model-inversion-based approach [15]-[20]; (b) high-gain feedback linearization [21], [22]; and (c) use of charge-amplifier rather than voltage amplifier [23]-[26].*

Traditionally, piezoactuators (piezos) have been used to achieve nanopositioning in typical SPMs. However, the range of piezo-based nanopositioners tends to be inversely proportional to the bandwidth — increasing the range leads to a reduction in the bandwidth (throughput), e.g., [27]. Therefore, recent research efforts in the controls community have focused on developing large-range high-bandwidth nanopositioning systems,

The proposed module will focus on the use of inchworm nanostepper to achieved both large range and high throughput [28]-[34] — see Figure 8 for the basic operating concept of an inchworm nanostepper for one step. Multiple steps leads to large motion. The proposed module on inchworm will consist of two parts: (i) analysis: modeling and control of piezo; and (ii) design: novel approaches to overcome the bandwidth-range limitation.

3) Analysis: In the first part, SPM-based nanofabrication will be used to motivate the need for nanopositioning systems and to introduce the use of piezos as sensors and actuators in nanopositioning systems. Models of an example piezopositioner in Dr. Devasia's lab will be used to illustrate the range vs bandwidth limitation. The use of control methods to reduce vibration-caused bandwidth limits will be introduced. It is noted that typical undergraduate control classes usually cover linear systems; in contrast nanopositioners using piezos have hysteresis nonlinearities. Challenges in the control of nanopositioners due to nonlinearities will be introduced along with current methods to address such nonlinearities as illustrated in Fig. 7. The in-class discussion will be followed with a homework (HW) problem where students will evaluate the potential increase in bandwidth achievable with control systems.

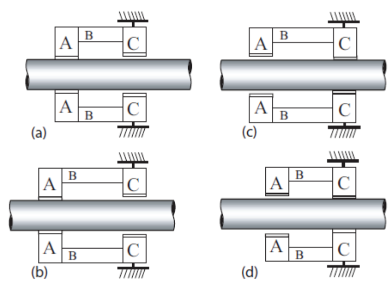

Fig. 8. One inchworm step to move a rod to the left. (a) piezo A clamps to the rod, (b) piezo B expand, (c) piezo C clamps and A releases, and (d) piezo B contracts.

4) Design: The second part of the module will begin with an in class discussion on potential design approaches to increase range of a system, such as human walking, where we make small steps but are able to travel large ranges. This will be followed by an open-ended HW problem where students will be asked to innovate, and design nanopositioning systems that mimic the human walking. After this second HW is turned in, potential approaches will be discussed in the class, leading to the introduction of nano steppers such as inchworm nanopositioners and its connection to human walking. Students will be asked to identify potential areas where control can still be beneficial, e.g., to control unwanted vibrations in the inchworm whenever it makes a step.

Thus, the inchworm module will be used to convey both analysis issues (modeling and control) and design issues (novel mechanisms to overcome range-vs-bandwidth limits) in nanopositioning systems.

F. ME498 Nanodevice Design and Manufacture; Lead: Prof. J. Chung

1) Overview: This new senior level course focuses on nanofabrication and molecular assembly methods. The proposed module will offer physical insights about the working principle of a nanotip sensor and offers hands-on-experience for designing a molecular enrichment system, which are the major research areas of Dr. Chung's current research projects [35], [36]. The outcomes impacted by this module are: (i) analysis (mechanics of nanotips); (ii) fabrication of nanotips and nanowires; and (iii) design and testing of nanotip molecular enrichment systems

2) The Nanotip Enrichment System Module: There is a substantial demand for nanodevices such as molecular enrichment systems for disease diagnosis and environmental monitoring because such devices play a key role to find biomarkers and discover drugs. It is noted that recent efforts in nanoengineering for biology have focussed specifically on how to enrich low-abundance molecules with high throughput. However, the specific enrichment performance of such systems has been hindered with a decrease in size because inertial effect is reduced with dominant viscosity. In addition, nonspecific binding forces increase rapidly as the scale is decreased to molecular dimensions. The proposed module will integrate into the undergraduate curriculum novel nanodevices that resolve this molecular-enrichment challenge. Topics covered will include: scaling issues in such nanodevices and innovative nanofabrication methods.

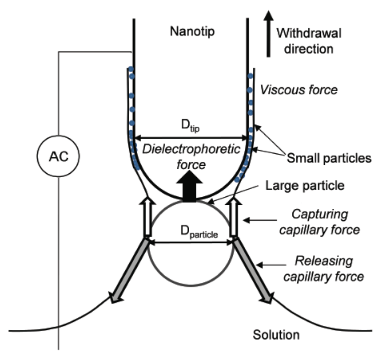

Fig. 9. Analysis: Mechanics of a nanotip in conjunction with capillary action, viscosity, electric field, and chemical binding affinity [35].

3) Analysis of nanotip enrichment system [35]: In this analysis (see Fig. 9), nanotips will be comparatively analyzed against larger-scale tips to motivate students to learn about the effects of different length scales and the advantages of nano-devices. The analysis will include the effect of different forces at different length scales. In particular, deterministic and probabilistic forces will be introduced with simple experimental demonstrations. For example, deterministic electric forces will be introduced along with probabilistic chemical binding forces and a discussion on how to balance such forces to design the efficient enrichment of molecules [35].

4) Fabrication of Nanotips [36]: In this lab, a nanotip (see Fig. 10) composed of hybrid materials will be fabricated by using capillary action and an electric field [36]. For material preparation, students will learn how to handle single walled carbon nanotubes and SiC nanowires along with safety issues involved in nanomaterial processing. The fabricated nanowires will be observed by a scanning electron microscope in order to understand the

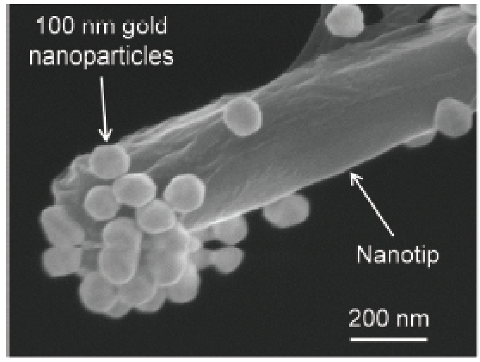

Fig. 10. Nanotip composed of carbon nanotubes and SiC nanowires fabricated in Dr. Chung's laboratory [36].

structural composition and orientation of nanostructures in conjunction with the force mechanics involved in the fabrication process. Through this fabrication laboratory exercise, students will be able to understand the design parameters and the underlying physics as well as their effects on the applications of the fabricated nanotubes and nanowires.

5) Design and Testing of Nanotip Molecular Enrichment Systems: In this lab, students will enrich nanoscale particles using nanotips that are fabricated in the previous lab session. In the enrichment step, students will use an electric field and capillary forces for attracting and capturing nanoscale particles. Optical microscope and fluorescence microscopes will be used to evaluate the achieved enrichment. Through this experiment, students will be able to understand the effects of deterministic- and probabilistic forces. Design issues will be studied on how to combine such forces for enhancing/optimizing the enrichment performance for different applications.

G. ME498 Biological Frameworks for Engineers; Lead: Prof. N. Sniadeck

1) Overview: This senior-level course is designed to smooth the learning pathways between the fields of engineering and biology and highlight the relationship between structure and function in biology systems from the meso-scale to the nano-scale. A new laboratory module is proposed to integrate the student's knowledge on protein mechanics, cell-matrix interactions, and cell movement as it relates to cell contraction. The module will use Dr. Sniadeckis nano-post arrays to measure cellular forces, which is the focus of his lab's current research. The educational outcomes from this laboratory experience will include: (i) analysis of nanoscale force sensors, (ii) fabrication of arrays of nanopost, and (ii) design of of a new sensor scheme that is appropriate to the contractile forces of different cell types.

2) The Nanopost Module: Cells rely on their ability to produce forces not only for locomotion, but to mechanically probe their environment and maintain contractility, which provides feedback in regulating their function. To measure cellular forces, we have engineered a substrate that has vertical cantilevers [37]-[44]. We fabricated arrays of closely spaced, vertical polydimethylsiloxane (PDMS) posts such that individual cells can attach and spread across multiple posts (Fig. 11A). We selectively coat extracellular matrix onto the tips of the posts using a micro-contact printing strategy that renders the tops adhesive, but the sidewalls and base non-adhesive. For small deflections, the posts behave like simple springs with deflection directly proportional to the force applied by the cell (Fig. 11B). We have previously made posts with microscale dimensions, (diameters $D = 2 - 3\mu$m, center-to-center spacing $S = 6 - 9\mu$m, and length $L = 6 - 14\mu$m), but we have recently produced arrays with nanoscale dimensions, see Fig. 12. Previous approaches to measure cell forces have used continuous surfaces like wrinkling silicone membranes or deformable gels [45], [46]. Our arrays, by the discreteness of individual nanoposts, allow for isolated measurements of traction forces at the individual focal adhesions of cells (Figs. 11C,12B,D).

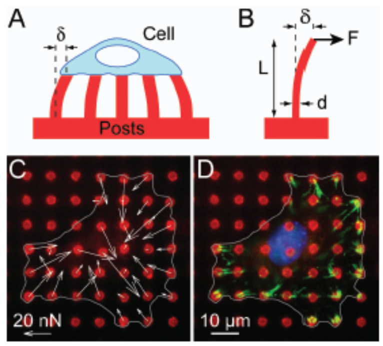

Fig. 11. (A) Cells spread across and deform arrays of PDMS posts. (B) Each posts deflects like a cantilever spring and tip force F is given by $F = \frac{3\pi D^4}{64L^3}\delta$. (C) Force vectors are calculated at each nanoscale focal adhesion by (D) vinculin staining.

3) Analysis: In the first part, nanoposts arrays will be used to motivate the need for mechanical force sensors that have sufficient force resolution and dimensions that are appropriate for cells and their subcellular protein structures. The length of a cell varies with its phenotype: for example, heart muscle cells are $100-200\mu$m and and platelets are $2-4\mu$m. In addition, a cells focal adhesion ($100 - 2000$nm) contains hundreds of smaller aggregated proteins that define the interface between cells and the matrix, which makes them essential for the transmission of contractile forces to the outside environment (Fig. 11D). A pre-lab homework assignment will be given for the students to: (a) examine the relationship between a post's dimensions and its spring constant; and (b) the limits of optical microscopy in resolving post deflections.

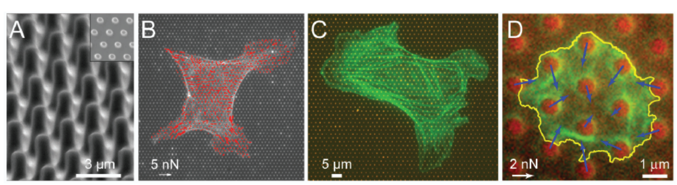

Fig. 12. (A) SEM image of nanoposts (inset: top-down image of array). (B) Higher packing density and smaller dimensions improve force vector resolution of 3T3 fibroblast traction forces and (C) promote actin filament organization. (D) Subcellular forces of an individual platelet.

4) Fabrication: In the second part, the students will gain hands-on experience performing the manufacturing of the nanopost arrays. With assistance from a TA and Prof. Sniadecki, the students will perform a soft-lithography procedure so as to replicate a silicon array (master) into many identical PDMS arrays for testing. The TA will then plate fibroblast cells onto the

PDMS arrays and the students will measure the deflections of the posts by the cells under a fluorescence microscope and MATLAB's image analysis toolbox. An in-lab discussion will take place on the capabilities of different lithography and nanofabrication techniques, manufacturing tolerances in PDMS soft-lithography, and surface chemistry involved in micro-contact printing. For the report, the students will be asked to describe the fabrication process for the silicon and PDMS arrays, the physics of the methodology used, and the results of measuring cellular contractile forces.

5) Design: A post-lab homework assignment will be given for the students to innovate a new nano force sensor design and matching fabrication approach that is suitable for measuring the contractile forces of cells that Prof. Sniadecki's lab has previously analyzed: smooth muscle, endothelial cells, cardiomyocytes, fibroblasts, and platelets. Each cell type has different dimensions and also different magnitudes of contractile forces due to actin and myosin isoforms. Students will need to ensure that their designs have the proper dimensions and physics to resolve the forces under optical microscopy.

The educational outcomes of this module will fortify an understanding of nanoscale fabrication and design that is readily applicable to cell-based force sensors, but also gain knowledge in the physical interaction of cell with synthetic or natural biomaterials.

H. ME498 Mechanics of Thin Films; Lead: Prof. J. Wang

1) Overview: This senior level course currently focuses on thin film deposition processes, stress and microstructure development during film growth, mechanisms of adhesion, delamination and fracture of thin films devices. A module is proposed on the analysis, design and fabrication of nanoscale mechanical testing systems the specific nanodevice considered will be a nanoscale thin film tensile tester for characterizing mechanical properties of nanoscale thin films and multi-layers. The outcomes impacted by this module will include: (i) analysis (of the adhesion, delamination and failure of nanoscale thin films); (ii) design (of an nanoscale thin film tensile tester), and (iii) fabrication of the prototype of the proposed tensile tester.

2) The Nanoscale Thin Film Tensile Tester Module: Thin films play important roles in nano and microelectromechanical devices, magnetic storage media and surface coatings. With the rapid advances in nanotechnology, most of the constituent components in the nanosystems are essentially reduced to thin film form. Due to the well-recognized size effect, mechanical properties of nanoscale thin film tend to be different from that of their bulk counterpart and they have to be characterized at the exact length scale as used in the intended nanodevices.

Recent effort in nanoscale thin film characterization can be roughly grouped into two categories: nanoindentation/AFM (atomic force microscope) testing and in-situ electron microscopy testing [47]. Nanoindentation/AFM techniques are capable of probing the mechanical properties of thin films and nanoscale structures with high displacement and load resolution. However when the film thickness is in nanometer regime or the components involve multi-layers, these indentation based techniques face challenges in isolating the properties of the film from the substrate or surrounding multi-layers. The in-situ electron microscopy techniques (SEM or TEM) overcome this challenge by testing the nanoscale thin films in the free-standing form. The in-situ SEM/TEM methods require special loading stages that can be placed inside the

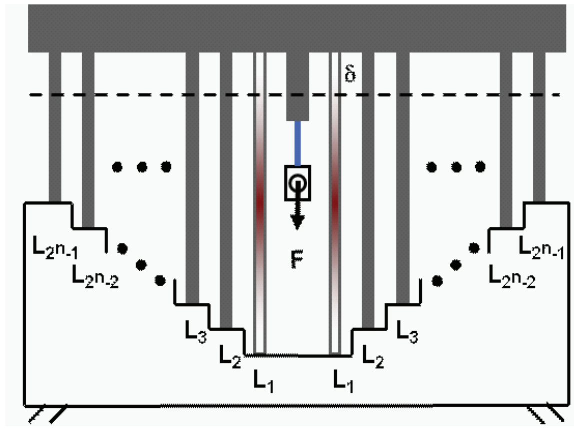

Fig. 13. Illustration of force-domain ADC. Force is digitized by the buckling beams. A n-bit F-ADC consists of $2^n - 1$ beams on each side of the testing structure. The total force applied in the thin film sample (in the middle) is the summation of the critical load in the bucked beams (e.g., L_1) and the elastic force in the rest beams, i.e., $F = 2\left(P_{crl} + \sum_{i=2}^{2^n-1} \frac{E\delta A_i}{L_i}\right)$.

SEM and TEM chamber [48]-[50]. Thus, the testing using these techniques tend to be time consuming and instrument costly.

The proposed module in this course will focus on developing an alternative nanoscale thin film tensile tester. For example, based on the idea of n-bit analog to digital converter, a n-bit force-domain analog to digital converter (F-ADC) (see Fig. 13), with nanofabricated buckling beams as the force digitizing mechanisms can be potentially implemented for obtaining high resolution load/displacement information during thin film tensile testing. While this n-bit F-ADC will be used as an example module, students will be encouraged to think of other mechanisms to potentially achieve a similar objective.

3) Analysis: At the beginning of this course, applications of thin films in a wide range of nanotechnology applications will be covered. Students will be introduced to the various thin film deposition/patterning processes, stress development during film growth, and the different mechanisms of thin film failure. They will be motivated to understand the importance of thin film mechanical characterization. Students will be asked to analyze the needs and potential challenges in evaluating the mechanical reliability (such as adhesion, delamination and fracture) of nanoscale thin films and coatings. Atomic scale thin film/multi-layer deposition using magnetron sputtering and mechanical characterization using nanoindentation available in Prof. Wang's laboratory will be used to further demonstrate the importance of nanoscale thin film deposition and the challenges in their characterization.

4) Design: Based on students analysis of the needs and challenges of nanoscale thin film deposition and characterization, students will be introduced to the example design of the n-bit F-ADC tensile tester. They will be further divided into groups. Each group will be asked to come out with either ideas to further improve the current design of the F-ADC (for example, adding mechanisms on the buckling determination) or other innovative design approaches for an alternative nanoscale thin film tensile tester. The design ideas of each group will be documented and presented in front of the whole class and feedback will be provided for further improvement and revision of the design.

5) Fabrication: Once the design is validated and finalized by the group members, the students will be encouraged to fabricate a prototype of the proposed tensile tester. For cases where the design is complicate enough that the prototype can not be completed within the reasonable time of the class, the teams will be encouraged to continue working on the project either as undergraduate research for credit or as their capstone design project later in ME495.

I. ME495 Capstone Design; Lead: All Investigators

1) Overview: Offering educational experiences that resemble what people need to do in the workplace prepares students for future tasks in non-school settings [51]. Engineering students are typically provided with such an open-ended real-world design experience in the capstone project as part of design experience requirements of the Accreditation Board for Engineering and Technology (ABET). Therefore, nanodevice-related projects will be offered in the capstone design class to provide students with a design experience that will prepare them for future work in emerging nanotechnologies. The investigators have routinely offered such research-related design projects for the capstone class in the past. Moreover, in addition to offering research-type projects to student groups, the P.I. (Dr. Devasia) also teaches the senior-level capstone design class (ME 495M) in mechanical engineering.

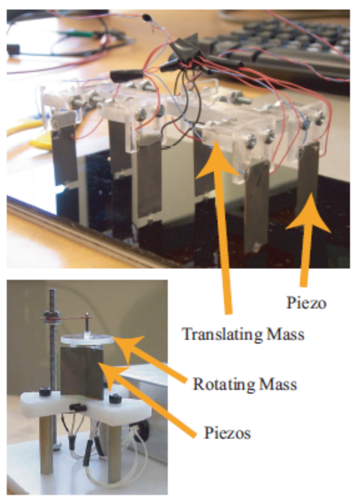

Fig. 14. Example research-type capstone design projects on rotary (bottom) and translational (top) nanosteppers using piezos. These projects were presented in the COE Open House to visiting high-school students .

2) Design of Nanodevices Module: In addition to the traditional objectives of a capstone design class (such as developing the ability to work in multidisciplinary teams), the goal is to provide real-world type design experience in nanodevices. Examples of such research-oriented undergraduate projects in the capstone design class are the design of rotary and translational nanosteppers used in nanopositioning systems shown in Fig. 14. The students investigated the effect of different driving waveforms on the suppression of vibrations and therefore on the increase in bandwidth for such positioners. Additional details are available at the website http://faculty.washington.edu/devasia/Teaching/Example_projects.htm. The investigators will offer such design projects related to their nanodevice research discussed in the previous sections.

These nanodevice projects will include: the design of nanogels for biomedical applications (Prof. A. Shen); design of nanofiber composites for solar cells, batteries and thermoelectric modules (Prof. J. Li); design of nanodevices for bio/chemical sensors and nanotip enrichment system (Prof. J. Chung); design of novel nanosteppers for nanopositioning systems (Prof. S. Devasia); design of nanoposts for nanoscale biological studies (Prof. N. Sniadecki); and nanoscale thin films testers (Prof. J. Wang).

IV. Evaluation Plan

The evaluation and assessment activities will be conducted through the Center for Engineering Learning & Teaching (CELT) at the University of Washington in coordination with project faculty. Additionally, the Mechanical Engineering External Advisory Board will provide the external (third-party) evaluation of the project. It is noted that this advisory board, comprising of industrial and (external) academic leaders, provides similar evaluations as part of the ME department's ongoing curriculum evaluation process for accreditation by the Accreditation Board for Engineering and Technology (ABET).

A. *Overview*

The evaluation and assessment plan will inform the effectiveness of the proposed nanodevices course modules in promoting student learning and in the achievement of program outcomes, and doing so in a way that is extensible to curriculum in the broader engineering education field. The assessment plan is integral with and dependent upon specific elements of the curriculum design and will be developed in coordination with nanodevices curriculum faculty team. The plan will include the gathering of learning, course, and program assessment data. Data will be both summative (measures of success) and formative, which are intended to provide the faculty team with opportunities to implement and document ongoing program and module improvements. Assessments are planned for the following purposes:

- To evaluate levels of student learning
- To determine the overall level of success of the nanodevices curriculum project
- To provide formative feedback for making improvements to individual modules and to improve the process of adopting and incorporating modules within mechanical engineering courses

CELT will coordinate these assessment activities with the faculty team, who will provide reports for the Mechanical Engineering External Advisory Board to conduct semi-annual programmatic review.

B. *Nanodevices Module Assessments*

The effectiveness of the nanodevice modules is dependent upon two factors: do the modules promote the intended learning, and are the modules sufficiently well designed to enable appropriate integration into courses. Specific learning assessments will be developed for each module that include methods (e.g. test questions/problems, homework or lab assignments, design projects) as well as a list of specific criteria (a rubric) for evaluating level of student performance. Rubrics will be refined and calibrated during the first year and included as important components of the refined curriculum in the second year. The design of learning assessment methods and module learning activities will be determined through a rational design process using Finks *backward design* method [52]. The first step is to identify each module learning objective (based on Figs. 1, 2), and then to determine what the best evidence would be that students had effectively mastered the objective. Learning activities will be tailored to help students achieve the desired learning and to produce that best evidence. In addition, both student and faculty formative feedback will be collected with end-of-module surveys of students and end-of-course surveys of faculty. Formative feedback and learning assessment data will be analyzed to determine level of success and to make specific refinements to the modules. Faculty will work closely with the CELT instruction and assessment specialist (Dr. Jim Borgford-Parnell) in evaluating data and determining appropriate changes. This approach not only systematically assesses what students know, but also promotes the principle of continuous pedagogical and course improvement.

C. Nanodevice Curriculum Project Assessment

Success of the overall project will be determined by evaluating how well the curriculum outcomes are achieved and by the ease with which the process of module integration is accomplished. Student learning assessment data (described in previous section) will be used to determine whether curricular outcomes are achieved. Learning assessment data are tied to specific module objective criteria, which in turn are linked to the overarching curriculum outcomes. Learning assessment data and student and faculty survey data will also be used to determine whether modules are appropriately sequenced in the nanodevices curriculum, and whether the development of additional modules is warranted. Data collected with the end-of-course faculty surveys will not only be used for continuous improvement of the modules, but will also help the faculty team in determining how to improve the process of module adoption and integration.

V. Acknowledgment

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