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CULLEN COLLEGE OF ENGINEERING
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MEMORANDUM OF UNDERSTANDING

Subject: **NanoEngineering Minor Option**

THIS MEMORANDUM OF UNDERSTANDING (MOU) is entered into as of September 25, 2008 by the Chairs of the Departments of Mechanical Engineering, Chemical & Biomolecular Engineering, and Electrical & Computer Engineering, the Dean of the Cullen College of Engineering and the Director of the NanoEngineering Minor Option (NEMO) program to ensure the efficient execution and the sustainability of the NEMO program.

Providing the NEMO program is established and remains in place, this MOU commits the respective departments to offer the NEMO core course sequence as specified below:

Department of Mechanical Engineering will offer "Introduction to Nanotechnology" lecture course concurrently with "Nanotechnology Laboratory" or agreed upon equivalents once a year for at least three years beginning in the 2009/2010 academic year. The preference will be given to offer the course in the fall semester.

Department of Chemical & Biomolecular Engineering will offer "Introduction to Nanomaterials Engineering" lecture course concurrently with "Nanomaterials Engineering Laboratory" or agreed upon equivalents once a year for at least three years beginning in the 2009/2010 academic year. The preference will be given to offer the course in the spring semester.

Department of Electrical & Computer Engineering will offer "Design and Fabrication at the Nanoscale" lecture course concurrently with "Nanofabrication Laboratory" or agreed upon equivalents once a year for at least three years beginning in the 2010/2011 academic year. The preference will be given to offer the course in the fall semester.

The above courses will be open to all engineering students subject to seating capacity and satisfying course prerequisites. The preference will be given to NEMO program participants to ensure timely completion of the program by the participants.

The Director of the NEMO program will provide a detailed report on the status of the NEMO program to the respective departments by the beginning of the fall semester of 2011/2012 academic year to enable program evaluation and to allow for necessary adjustments for continuing program viability.

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NanoEngineering Minor Option

Proposal

The high technology revolution, driven by the breathtaking success of semiconductor integrated circuits, has transformed world economies and will continue shaping the human enterprise for generations to come. The rapidly approaching end of the technology roadmap for semiconductors has prompted a number of nanotechnology initiatives to facilitate a transition into the era of nanoscale integrated systems. The innovative ideas resulting from these nanotechnology initiatives are being rapidly commercialized and new knowledge is being created. There exists a critical need to supplement traditional in-discipline training with interdisciplinary nanoengineering curriculum to address the needs of both emerging nanotechnology enterprises and rapidly forming nanoscale industries.

The addition of a NanoEngineering Minor Option (NEMO) to the undergraduate programs in the Cullen College of Engineering provides the following benefits to the students, the University of Houston, the industry, the academia, and the general public.

1. It increases the student employment options, as well as their income.
2. It increases the pool of engineering graduates available to meet a critical industry need.
3. It increases the pool of qualified graduates prepared to continue onto graduate studies.
4. By broadening the education base of graduates, it offers unique technical synergies to the nanotechnology industry.
5. It increases the pool of undergraduate engineering students, by providing them nanotechnology education, which is not presently offered at the University of Houston.
6. It meets a critical technical need of the US economy from inside the country.

The course requirements for the NanoEngineering Minor Option are:

MECE 5319 / ECE 5319 / CHEE 5319 Introduction to Nanotechnology
MECE 5119 / ECE 5119 / CHEE 5119 Nanotechnology Laboratory

MECE 5320 / ECE 5320 / CHEE 5320 Introduction to Nanomaterials Engineering
MECE 5120 / ECE 5120 / CHEE 5120 Nanomaterials Engineering Laboratory

MECE 5321 / ECE 5321 / CHEE 5321 Design and Fabrication at the Nanoscale
MECE 5121 / ECE 5121 / CHEE 5121 Nanofabrication Laboratory

CHEE / MECE / ECE 4398 Special Problems (Research)

Students choosing to minor in NanoEngineering must complete the above courses (total of 15 credit hours). The above lecture/lab courses, nanoengineering core sequence (see Appendix A), will substitute for elective course requirements in the respective departments. Furthermore, the program participants will enroll in one-semester special topic course (Appendix B) that will enable them to gain firsthand experience in conducting scientific research working side-by-side with the graduate students and faculty.

The minimum enrollment standards to participate in the program will include junior standing and a GPA of 3.0 or better. Initial class size will be limited to 25-30 students. Hence, the enrollment in the program will be competitive. The selection will be based on past academic performance and promise for engineering-related research as demonstrated by transcripts and an oral interview.

The development of the NEMO program is supported by a $200k Nanotechnology Undergraduate Education grant which will fund the two-year expenses for administering the program, purchasing of lab supplies, and $3000 research scholarships for 15 students per year.

APPENDIX A: NANOENGINEERING CORE SEQUENCE

A three-course nanoengineering sequence will build upon existing undergraduate courses taught by Sharma, Krishnamoorti, and Litvinov. The course contents will be coordinated to enable a structured nanoengineering curriculum as discussed below. Laboratory exercises will be developed for each of the three courses to provide students with hands-on experience in utilizing nanoengineering instrumentation as well as to deepen the understanding of the nanoscience and engineering concepts discussed during lectures. Laboratory exercises will prepare the NEMO students for research experience and nanotechnology focused capstone design course, which are the integral part of the NEMO program.

I.1 INTRODUCTION TO NANOTECHNOLOGY (MECE/ECE/CHEE 5319 LECTURE + MECE/ECE/CHEE 5119 LAB)

"Introduction to Nanotechnology" will serve as a leveling course to familiarize beginning NEMO undergraduate scholars with the fundamental concepts underlying various nanotechnologies. The course will be based on conventional classroom instruction supplemented with laboratory exercises and will cover the following topics:

Topic	Outline
Introduction to nanophysics	Brief introduction to quantum mechanics and materials physics; effects of reduced dimensions on physical, chemical, and mechanical properties of materials and devices
Overview of nanodevices and materials	General discussion of nanoelectronics/devices, quantum dots, quantum computing, nanotubes and nanowires, nanomaterials in general, nanocomposites, nanomechanical systems, and thin films
Fabrication at nanoscale	Introduction to lithography fundamentals; optical and e-beam lithography; discussion of resolution limits; challenges of pattern transfer at nanoscale
Nanoscale metrology	Instrumentation for nanoscale measurements; challenges due to the absence of appropriate metrology standards; fundamental resolution limits

Laboratories will include 4-5 supervised exercises to utilize nanotechnology tools including atomic/magnetic force microscopy, scanning electron microscopy, e-beam lithography to generate simple device patterns. The in-lab exercises where the students will collect data (e.g. topographic images of nanostructured arrays) will be complemented with off-line analysis (e.g. evaluation of size distribution of images nanostructures) of the data and preparation of formal reports.

Expected course outcomes: Students who have successfully completed "Introduction to Nanotechnology" will be expected to meet the following course outcomes:

- Students will add to their knowledge-base basics of device and materials physics in systems with reduced dimensions.
- Students will gain basic understanding of the motivation behind the transitioning to nanotechnology with respect to device and materials performance.
- Students will have basic understanding of modern fabrication technologies and approaches to metrology at nanoscale.
- Students will receive hands-on experience in utilizing state-of-the-art nanotechnology instrumentation and gain skills in advanced data analysis.
- Students will receive sufficient background knowledge and develop experimental skills to take on more advanced topics that will be presented in the following courses within the nanoengineering core.

I.2 INTRODUCTION TO NANOMATERIALS ENGINEERING (CHEE/ECE/MECE 5320 LECTURE + CHEE/ECE/MECE 5120 LAB)

"Introduction to Nanomaterials Engineering" will provide a detailed account of the advantages of nanomaterials including nanocomposites, ceramics, materials based on polymer matrices, as well as give an insight into synthesis and characterization of nanomaterials. The course will cover the following topics:

Topic	Outline
Materials engineering at nanoscale	Nanostructured semiconductors, metals, ferromagnetics, ferroelectrics, molecular and macromolecular materials
Synthesis of nanostructured materials	Nanocrystalline thin films, nanocomposites, nanoparticles, superlattices, polymer matrices
Novel forms of carbon	Fullerines (buckyballs, nanotubes, graphine): promise and challenges
Nature inspired materials	DNA based molecular networks, nanowires, photosensitive proteins
Bottom-up materials engineering	Soft materials and ceramics; self-assembly, hierarchical structures, mesoporous hybrids

Laboratory exercises will include 3-4 supervised synthesis and characterization of a model set of nanomaterials including (magnetic) nanoparticles, carbon nanotubes (using chemical vapor deposition), electrochemical de-alloying to form ultra-high surface area porous materials. Similar to the above, the in-lab exercises where the students will synthesize and characterize nanomaterials will be complemented with off-line data analysis and preparation of formal reports.

Expected course outcomes: Students who have successfully completed this course will be expected to meet the following course outcomes:

- Students will add to their knowledgebase in the major areas of nanomaterials engineering including nanostructured semiconductor and magnetic materials, ceramics, ferroelectrics, and organic semiconductors.
- Students will have understanding of major approaches to nanostructured materials synthesis.
- Students will gain basic understanding of approaches to tailoring nanomaterials functionalities.
- Students will gain hands-on skills and experience in nanomaterials synthesis and characterization.
- Students will have sufficient basic knowledge on nanomaterials to study more advanced topics and to effectively handle the following nanodevice course.

I.3 DESIGN AND FABRICATION AT NANOSCALE (ECE/MECE/CHEE 5321 LECTURE + ECE/MECE/CHEE 5121 LAB)

"Introduction to Design and Fabrication at Nanoscale" will capitalize on the knowledge-base built in the two previous courses and will discuss nanotechnology advantages and issues with respect to novel devices and systems, approaches and challenges in device fabrication and integration at nanoscale. The course format is based on conventional classroom instruction with up to four invited lectures delivered by the UH experts on specific topics. Conventional homework assignments will be mixed with open-ended problems, for example, analysis of scientific and engineering journal articles. The coursework will also include an assigned project designed to analyze state-of-the-art in a specific sector of nanotechnology. The course will cover the following topics:

Topic	Outline
Fabrication at Nanoscale	E-beam lithography, imprint lithography, ion/atom beam lithography, focused ion-beam lithography, self-assembly: advantages and challenges
Logic devices	Scalability of silicon-based MOSFET's, carbon nanotube logic, spintronics, molecular electronics, quantum cellular automata, quantum computing
Random Access	Ultra-small DRAM, Flash Memory, ferroelectric RAM, Magnetoresistive RAM

Memories	
Mass Data Storage Systems	Ultra-high density hard disks, MEMS-based probe storage, holographic data storage, protein-based storage
Sensors and Sensor Arrays	Optical sensors (from IR to UV), magnetic field sensors, sensors for chemical and biological applications
Displays	Organic light emitting devices, field emission and plasma displays, electronic paper

Laboratory exercises will include 3-4 supervised fabrication of model nanoscale device structures, which will include thin film deposition (semiconductor or magnetic), patterning of device structures using electron-beam lithography, and characterization of patterned devices using scanning probe microscopy and aggregate testing of electronic/magnetic properties. These exercises will be conducted in the NEMO faculty research labs and recently built nanofabrication facility and are enabled by ongoing extensive nanofabrication research conducted at the College of Engineering by the NEMO faculty.

Expected course outcomes: Students who successfully complete this course are expected to meet the following course outcomes:

- Students will add to their knowledge base in major areas of nanoengineering: quantum devices, nanomagnetics, molecular electronics, nano/bio sensors.
- Students will have understanding of major approaches to fabrication and characterization of nanostuctures and devices.
- Students will improve their abilities in technical literature mining and understanding.
- Students will gain insight and develop practical skills necessary for nanodevice design and fabrication.
- Students will receive sufficient background knowledge in key aspects of the above mentioned nanotechnologies to understand more advanced literature and be prepared for further study.

APPENDIX B: RESEARCH PROJECT (CHEE/MECE/ECE 4398)

As part of the NEMO minor, NEMO scholars will participate in a semester-long research project working side-by-side with graduate students and faculty at the College of Engineering. The goal of the research projects is to provide the NEMO scholars with an opportunity to design and build a device or a system incorporating elements of nanotechnology.

The technical expertise of the faculty mentors listed below, along with others, will provide NEMO scholars with the opportunity to work in world class research labs under the guidance of nationally-recognized leaders in the field of nanotechnology with a demonstrated interest in synergistic activities.

- Dr. Shankar Chellam is a Professor of Civil and Environmental Engineering. His work focuses on quantifying hindered diffusion and convection of bacterial and viral pathogens across microfilters and ultrafilters, and employing nanofilters to remove trace organic contaminants.
- Dr. Vincent Donnelly is a Moores Professor of Chemical and Biomolecular Engineering. His current areas of research include plasma processing of materials, plasma diagnostics, plasma-surface interactions and nano-fabrication methods. He has published over 150 papers and holds ten patents.
- Dr. Demetre Economou is a Moores Professor of Chemical and Biomolecular Engineering. His research interests include plasma science for electronic materials processing at nanoscale. He co-authored of over 130 papers and book chapters in these areas.
- Dr. Fazle Hussain is a Cullen Professor of Mechanical Engineering. His research is focused on turbulent flows, vortex dynamics, jets and boundary layers, aeroacoustics, optical measurement techniques, fluidized beds, bio-fluid dynamics, and applications of the above concepts to nanofluidics.
- Dr. Ramanan Krishnamoorti, a Professor of Chemical and Biomolecular Engineering, is investigating

polymer crystallinity in bulk and thin films, thermodynamic interactions and viscoelasticity of polymer blends and copolymers, macro and nanocomposite structure and viscoelasticity.

- Dr T. Randall Lee is a Professor of Chemical and Biomolecular Engineering and Chemistry. He is a leader in self-assembled nanoparticle growth and manipulation.
- Dr. Dan Luss is a Cullen Professor of Chemical and Biomolecular engineering. His research is focused on dynamic features of chemically reacting systems, such as reverse-flow reactors, hot-spot formation in packed-bed reactors to form novel nanostructured materials.
- Dr. Dmitri Litvinov is a Professor of Electrical and Computer Engineering and of Chemical and Biomolecular Engineering. His research interests include nanomagnetic materials and devices for future magnetic storage technologies, magnetic RAM and logic, magnetic biosensor arrays.
- Dr. Paul Ruchhoeft is an Associate Professor of Electrical and Computer Engineering. His research interests lie in nano-fabrication using ion/atom beam proximity lithography, reactive ion etching, thin-film deposition, and stencil mask technology for low-cost, large-area periodic nanostructures.
- Dr. Pradeep Sharma is an Associate Professor of Mechanical Engineering. His interests lie in coupled strain-quantum mechanical behavior in quantum dots and defects, nanoscale piezoelectricity, size-dependent elasticity, nanomechanics of defects and inclusions.
- Dr. Gangbing Song is a Professor of Mechanical Engineering. His research is focused on novel multifunctional materials including shape memory alloys and piezoceramics for aerospace, biomedical, nanopositioning, and oil exploration applications.
- Dr. Richard Willson is a Professor of Chemical Engineering and Biochemistry and Biomedical Engineering. His research focus is on single molecule based biodetection for medical applications.
- Dr. Jack Wolfe is a Professor of Electrical & Computer Engineering. He is the co-inventor of massively parallel direct-write atom beam lithography. His current areas of research are atom/ion beam lithography, ultra-high resolution resist development, integrated circuit metallization.

Examples of the topics and associated project descriptions are given below:

Example Project 1: *Atom-Beam Nanolithography for Manufacturing Large Areas of a New Class of Membrane Filters*

The NEMO team involved in this project will fabricate and characterize water filters for separating bacterial and viral contamination from water sources under the supervision of a graduate student mentor. The students will develop a research plan, where a number of filters will be fabricated with pre-defined process variations. Following membrane fabrication using ion-beam lithography system, the NEMO students will learn how to use state-of the art equipment to measure its pore size distribution as a function of process variables using a combination of electron microscopy and digital image analysis as well as gas-liquid porometry. The undergraduate student will also quantify the performance of the filters in terms of pure water permeability, viral, bacterial, and yeast removal by using an existing bench-top filtration apparatus. The students will be required to effectively communicate their ideas to the research team through periodic oral presentations and a written report.

Example Project 2: *Magnetic Information Storage Using Nanoscale Magnetic Patterned Media*

The NEMO team will participate in the fabrication and testing of patterned media. The team will use a UHV sputter deposition system to fabricate the magnetic films, atom beam lithography to define the patterns and sputter etching to form the bits. The students will use scanning electron microscopy (SEM) to evaluate the physical characteristics of the structures and a suite of tools, magneto-optic Kerr effect microscopy (MOKE), vibrating sample magnetometry (VSM) and magnetic force microcrosopy (MFM), to evaluate the magnetic properties of the samples. The team will use design-of-experiment (6σ) methods to optimize thin film growth and media fabrication processes. Students will make biweekly presentations to the nanomagnetics research group and prepare final report.

Example Project 3: *Nanomagnetic Detector for Biomolecular Recognition*

NEMO students involved in this project will contribute to the fabrication of a magnetoresistive sensor array with sub-100 nm cell-size, with the cell geometry optimized for 100nm nanoparticle detection. Student will take part in the study of the magnetic interaction between a nanoparticle and a sensor element using a nanopositioning magnetic probe. Upon labeling of target DNA and proteins with magnetic nanoparticles and comparison with well-characterized model systems, the potential of parallel magnetic pull-off "melting curves" for efficient differentiation against non-specific association will be evaluated. The students will be exposed to conventional integrated circuit fabrication techniques, focused-ion beam lithography, nanomanipulation, scanning probe microscopy, electronic characterization of magnetoresistive circuits, and biomolecular functionalization techniques.

Example Project 4: *Nanopantography*

The NEMO team will test the ultimate resolution of nearly atomic dimensions, nano-Einzel lenses with diameter of 40 nm or less fabricated using ion beam proximity printing. The NEMO scholars will work with a graduate student mentor to fabricate Einzel lenses by ion beam lithography. The students will investigate ultimate resolution by ion trajectory simulation and experiments. The students will examine the effect of ion impact energy, substrate temperature and roughness on achievable resolution. The students will learn to use Scanning Electron Microscopy and Atomic Force Microscopy to examine deposits. First, we plan to apply this method to deposit small metal particles that will nucleate the growth of an ordered array of isolated, vertically aligned carbon nanotubes, for field emission applications.

Expected course outcomes: Students who have successfully completed this course will be expected to meet the following course outcomes:

- The students will add to their ability to identify and formulate engineering problems and apply knowledge of nanoengineering to design and built a model nanotechnology-based system.
- The students will improve their ability to design and conduct experiments, analyze and interpret data.
- The students will develop an ability to design a system or component to meet desired needs.
- The students will gain experience to function in multi-disciplinary teams.
- The students will improve their ability to communicate effectively.

CATALOG LANGUAGE:

Nano Engineering Minor

Students who choose to minor in Nano Engineering must complete 15 hours in Nano Engineering including ECE / CHEE / MECE 5319, 5119, 5320, 5120, 5321, 5121. Prerequisite and/or corequisites must be observed and will be enforced.

The students must also complete ECE / CHEE / MECE 4398 special problems course conducting supervised research on a Nano Engineering project approved by the Nano Engineering minor advisor in the Cullen College of Engineering.

Students should consult the Academic Regulations and Degree Requirements section of this catalog for general information on the requirements for minors and contact the Nano Engineering minor advisor in the Cullen College of Engineering.

Students must earn a 3.00 minimum cumulative grade point average on all courses attempted in the minor discipline at the University of Houston. No course may count toward the minor in which a grade of less than **C–** is earned.