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Integrated Sensing and Information Processing Theme-Based Redesign of the Undergraduate Electrical and Computer Engineering Curriculum at Duke University

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ABSTRACT

The field of electrical and computer engineering has evolved significantly in the past two decades. This evolution has broadened the field of ECE, and subfields have seen deep penetration into very specialized areas. Remarkable devices and systems arising from innovative processes, exotic materials, high speed computer simulations, and complex algorithms make ECE an exciting career field. These fascinating developments present greater opportunities for undergraduates to explore the field of ECE as well as greater challenges for them to navigate the curriculum because of the myriad of course and areas of concentration choices they have to make. Reflecting innovations in the field and capitalizing on the collective faculty research expertise, the Department of

Electrical and Computer Engineering at Duke University has redesigned its undergraduate curriculum around the theme of *Integrated Sensing and Information Processing*.

This paper presents details of the ECE curriculum redesign at Duke University including its philosophy and implementation as well as elements of the redesign that are transferable to other universities. Evidence of increased student ability to design a system or component and to work effectively in teams is presented through statistical analyses of student end-of-course course evaluations. Student design project complexity evolution as the curriculum redesign unfolded is also presented, and this provides further evidence that design and teamwork have enhanced student learning throughout the new curriculum.

Key Words: Department Level Reform, Theme-based curriculum redesign, Integrated Sensing and Information Processing

INTRODUCTION AND MOTIVATION

This paper presents details of the ECE curriculum redesign at Duke University including its philosophy and implementation, as well as elements of the redesign that are transferable to other institutions. Evidence of increased student learning is presented through statistical analyses of student end-of-course course evaluations and an examination of design project complexity evolution as the curriculum redesign unfolded. Assessment results also indicate areas of the curriculum that need improvement, and plans for ongoing, continuous improvement are outlined.

In the 1990's several anecdotal statements made by ECE students expressing appreciation for course projects and a sense of disconnectedness between courses, combined with trends in end-of-course surveys supporting those statements, prompted a methodical approach by the ECE Department at Duke to assess the state of its undergraduate program. This formal assessment commenced in 2000 with 1) a private sector (Acuity Edge) educational consultant who performed in-depth focus groups with ECE students at all levels, 2) analysis of several forms of course, instructor and laboratory surveys, 3) course/lab content review by an industrial advisory board, 4) course/lab content review by the collective ECE faculty, and 5) analysis of surveys of exiting seniors and alumni. This review process, which could be implemented at any institution for any program, proceeded for a period of two years leading to the identification of six critical areas needing development and improvement: 1) the curriculum needed a coherent, overarching framework that linked principles of ECE to each other and to real-world engineering problems, 2) students needed more guidance through broader exposure to ECE early in the curriculum to assist students navigate the technical areas of concentration and more ongoing guidance throughout their undergraduate experience as their career aspirations mature, 3) the curriculum needed to present a more balanced coverage and exploration of fundamental areas of ECE, 4) technical elective selection flexibility needed to be enhanced to provide greater latitude for breadth/depth opportunities, 5) design opportunities should be broadened, and laboratory experiences should be less prescriptive, and 6) computational tools needed to be better integrated across courses.

Concurrent with the extensive assessment of the undergraduate ECE curriculum during the period spanning 2000–2002, a few faculty members were experimenting with the integration of projects that linked their lecture with a project and/or design experience. For example, in the signals and systems course, the instructor had students build an AM radio from an Elenco kit, analyze the envelope detector circuit using the computer simulation package SPICE, and required students to write a project report. This project experience was linked to the lecture by cross-referencing the theory developed in class with the functions performed by the electronic components and subsystems of the AM radio. Other faculty members were exploring the educational literature and found that a substantial body of evidence was emerging that indicated that effective engineering student learning suggests: 1) early focus on real-world problems [1], 2) laboratory experiences should include design-oriented projects and reduced formulaic and prescriptive content [2], 3) student engagement on a global scale can be increased through effective use of active learning techniques and innovative use of technology [3], 4) there are three central topics of ECE (electronics, systems/information processing, computer science) [4], and 5) engineering education must be relevant to students' lives, attractive to students with diverse backgrounds, and connected to the needs of the broader community [5]. These elements of effective pedagogy in ECE are universal and can be used to guide curriculum reforms at other institutions.

In response to the extensive assessment of its undergraduate program and consideration of the emerging body of literature evidencing methods for improving engineering student learning, the ECE Department at Duke University committed to redesign its curriculum around the theme of *Integrated Sensing and Information Processing* (ISIP). The ISIP theme-based approach to the curriculum redesign continues to unite the entire faculty by directly connecting their collective research expertise with their course content and providing motivation to understand and contribute to the content of courses feeding their own course and to those courses that follow. The ISIP theme provides a coherent, overarching framework that links principles of ECE to each other and to real-world engineering problems. Several themes were considered for the curriculum redesign at a faculty retreat. After extensive deliberation, the collective faculty voted to align all of our undergraduate courses around the ISIP theme because it simultaneously captivates individual and collective faculty research expertise and the fundamental areas of ECE for the foreseeable future [4]. The theme-based approach may be effectively utilized at other institutions, but the specific theme would need to reflect the unique research strengths of the particular department's faculty. The term 'alignment' in the context of aligning courses with the ISIP theme refers to providing students with a holistic view of ECE through exploring concepts spanning how to interface sensors and systems with the physical world, how to transfer/transmit energy/information, and how to extract, analyze and interpret information. The first course in the new ECE curriculum and its cornerstone, Fundamentals of ECE, addresses all of these dimensions [5]. The degree of alignment by other courses to the ISIP theme depends on the subject matter and the creativity of the instructors. The ISIP theme integrates lateral and vertical connections among courses through thematic examples examined in class and projects performed in the laboratory.

The timing of the decision (2002) to redesign the ECE undergraduate curriculum coincided with the first cohort Departmental Level Reform (DLR) solicitation by the National Science Foundation (NSF). The ECE Department applied for and received a one-year planning grant in 2003 and a three-year implementation grant in 2004 (PI: L.M. Collins). Other EE/ECE programs have received NSF sponsored DLR grants and performed innovative and extensive curriculum revisions including the University of North Texas (PI: Varanasi) [7], the University of Utah (PI: Furse) [8], Oklahoma State University (PI: Cheville) [9], Kansas State University [10], and Iowa State University (P.I. Rover) [11]. A major report sponsored by NSF, written and published by the Science and Technology Policy Institute (STPI), provides a global evaluation of NSF DLR grants [12].

The implementation of the redesigned ECE curriculum at Duke began in the spring semester of 2006 with a pilot offering of the new curriculum cornerstone course, *Fundamentals of ECE,* and a full core offering in the fall of 2006. As the new core curriculum continued to evolve, existing and newly created upper-level technical electives, including design courses, were aligned by individual faculty and their associated Curricular Group with the philosophy and ISIP theme of the redesign. Other institutions could perform a similar thematic curriculum alignment process centered on the theme that best fits their faculty expertise.

The ECE faculty at Duke is categorized into Curricular Groups based on their respective area(s) of expertise. These Groups are Computer Engineering; Sensing and Waves; Microsystems; Photonics; and Signal Processing, Communications and Control Systems. Some faculty members belong to more than one Group due to the interdisciplinary nature of their research. The Faculty Groups have oversight responsibility for the courses that are taught by their faculty and play an essential role in the continuous improvement process of these courses by evaluating the degree to which course-level measurable outcomes are being attained and providing appropriate feedback to individual instructors. This ongoing process is performed in concert with the Undergraduate Studies Committee, which is comprised of faculty representatives from each of the Groups. Every major step of the curriculum redesign was overseen by a group of faculty members, and when appropriate, the membership of these groups included faculty from other departments to provide unbiased input. A similar organization of Faculty Groups and continuous improvement process could be implemented at other institutions depending on the specific expertise of individual faculty members.

CURRICULUM REDESIGN PHILOSOPHY

The objective of the curriculum redesign was to create the best possible undergraduate curriculum for ECE students at Duke University. There were several aspects of the undergraduate curriculum that were uniformly recognized as outstanding by all constituents. One goal of the curriculum redesign was to preserve these key features of the existing curriculum. These outstanding program elements include a highly flexible curriculum allowing students to pursue a wide variety of curricular and extracurricular activities enabling a tailored, personal educational experience. Approximately 25% of our students participate in a study abroad experience; this reflects one of the highest rates in the nation (national average for engineering in 2009 is 3.1% [13]). Our students are highly motivated to make a difference in the world by solving problems that help people. Engineering service participation in organizations such as Engineers Without Borders and Engineering World Health is on the rise. Hands-on research experiences are a hallmark of a Duke engineering education and enthusiastically supported by our faculty. More than 40% of our students participate in research through independent study including the premiere Pratt Research Fellows Program. More than 50% of students majoring in ECE pursue a second major either in another engineering field such as biomedical or mechanical engineering, computer science, a life or physical science such as biology, physics or chemistry, or a liberal art such as public policy, economics or even French Literature. These examples illustrate valuable curricular and extracurricular activities that students pursue as a result of our ECE curriculum flexibility. Our faculty determined that the best way to redesign the curriculum while preserving the unique and valuable experiences available to students through a flexible curriculum was to thread the ISIP theme through every course in the curriculum from the very first course through the remaining core courses and the technical electives including culminating design experiences. The ISIP theme reflects the active research areas of the majority of the ECE faculty, embodies the key concepts of all critical components of ECE, and broadly reflects the current state and future of the field. The ISIP theme-based structure enables coherent, lateral and vertically integrated connections between each course. These connections provide immediate relevance to what students are learning, increasing their interest and engagement. A thematic curriculum redesign approach could provide similar program improvements at other institutions.

Project-based learning (PBL) of engineering has received significant attention in the literature world-wide recently as an effective vehicle for providing exciting, relevant and meaningful contexts for learning engineering concepts [14]. PBL enables students to practice self-directed learning, which naturally leads to life-long learning. By placing the responsibility of learning on the student, it promotes the ability to adapt to change [14]. The ability to adapt to change is vital to the success of engineers in the 21st century [15]. One of the goals of the curriculum redesign was to establish lab experiences for *all* core courses with tightly-coupled integration between lecture and lab. The term "tightly-coupled" in the context of "tightly-coupled integration between lecture and lab," refers to bidirectional usage of content and pedagogy utilized in each portion of the course and leveraging this bidirectional usage to solidify conceptual understanding, extend the capacity for project functionality and to provide a clear linkage that fuels student's passion for learning. The term "project-based learning" refers to sequentially connected activities that require significant use of the tools learned in the course and prerequisite chain that provide relevance to the course content and lead to a culminating product.

All core courses now have significant laboratory components consistent with ISIP theme-based projects and varying degrees of open-ended design. "Open-ended design" implies that the design solution has elements that are not closed to further development. For example, a robot that must detect the location of a magnet has a multitude of solutions, many of which can be refined (e.g. cost, speed of detection) indefinitely. Hence, the students are confronted with the decision as to when their solution is refined enough to meet constraints imposed by both the instructor and by their team. Furthermore, *Fundamentals of ECE* and upper-level technical elective courses are incorporating open-ended projects including project management skills such as the use of Gantt charts for planning and strategizing by breaking down the project into a series of well-organized tasks, each of which can be tackled by small groups of students who are part of a larger team. Different combinations of students may work on multiple tasks. One of the main reasons why our students are now able to produce much more complex culminating design projects than they were prior to the curriculum redesign is because they have been developing their project-based learning skills including project management throughout the *entire* curriculum.

REDESIGN OF THE CURRICULUM

Core Curriculum Redesign and Alignment of Technical Electives with ISIP Theme

There were three main objectives of the **core** curriculum redesign; 1) develop an ISIP theme-based first course, *Fundamentals of ECE*, that provides a broad, holistic, yet rigorous introduction to ECE that includes a meaningful, open-ended design experience as well as a roadmap for the entire curriculum, 2) deconstruct and reconstruct the core curriculum to provide more balanced consideration of the three central topics of ECE [4], and 3) develop hands-on, ISIP theme- and project-based lab experiences for all core courses with open-ended design and project management skill development as appropriate for the specific course.

Figure 1 illustrates the structure of the ECE core curriculum before and after the curricular redesign. The colors indicate relative coverage of a given ECE topic. For example, green is used to indicate circuits (with darker green indicating devices), purple represents signals and systems, blue indicates digital systems (with darker blue indicating computer architecture), red represents electromagnetics and yellow indicates group-based project design.

Prior to the redesign, the first course was *Introduction to Electric Circuits*, which had a highly prescriptive lab with standard experiments that exercised the use of test and measurement equipment in the context of verifying DC and AC circuit principles. Examination of ECE curricula at other institutions revealed that *Introduction to Electric Circuits* is still the predominant front-end to most ECE programs. However, there are some interesting innovations in the first EE/ECE course that have emerged. Georgia Tech instituted a new introductory course based on the book, *DSP First*, written by J.H. McClellan et. al. [16] and introduces EE through digital signal processing. In fact, there has been a trend in the introduction of EE/ECE through signal processing first [17,18], and Padgett from Rose-Hulman Institute of Technology provides a cogent argument for transitioning from Circuits to DSP [19] as the foundation on which to build an EE/ECE curriculum. Some institutions offer a first

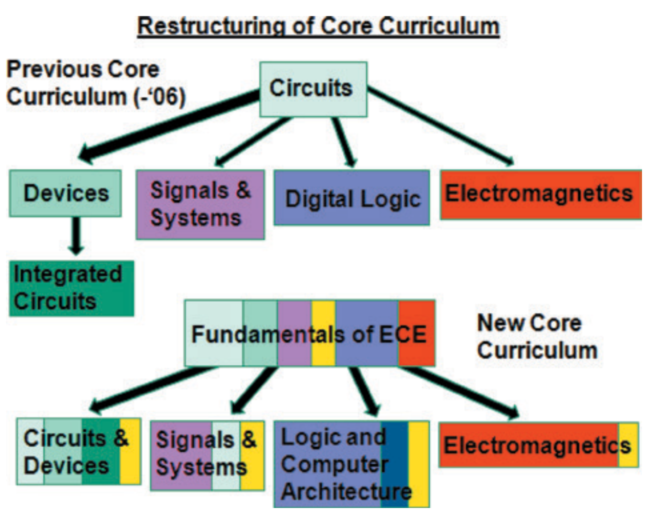


Figure 1. ECE Core curriculum before and after redesign.

course blending circuits, devices and systems, but these courses are generally intended for non-EE/ECE majors. Rice University offers *Fundamentals of Electrical Engineering I* that builds an EE curriculum on a foundation of signals and systems combined with analog and digital communications [20]. Thus, the trend away from circuits as the singular foundation of a modern EE/ECE curriculum is being established at numerous institutions.

The entire ECE curriculum is illustrated in Figure 2. Following the five ECE core courses are seven technical electives. Four of these ECE technical electives must be selected from at least two Areas of Concentration (Photonics; Computer Engineering; Electromagnetic; Signal Processing, Communication and Control Systems; and Microelectronics) to ensure depth and breadth. There are two additional ECE Technical Electives and an ISIP theme-based design course.

From *Circuits* to Fundamentals *of ECE* as the Cornerstone of the Curriculum

The content of the *Introduction to Electric Circuits* course at Duke was used primarily as prerequisite material for the *Introduction to Electronics: Devices* course, which in turn provided

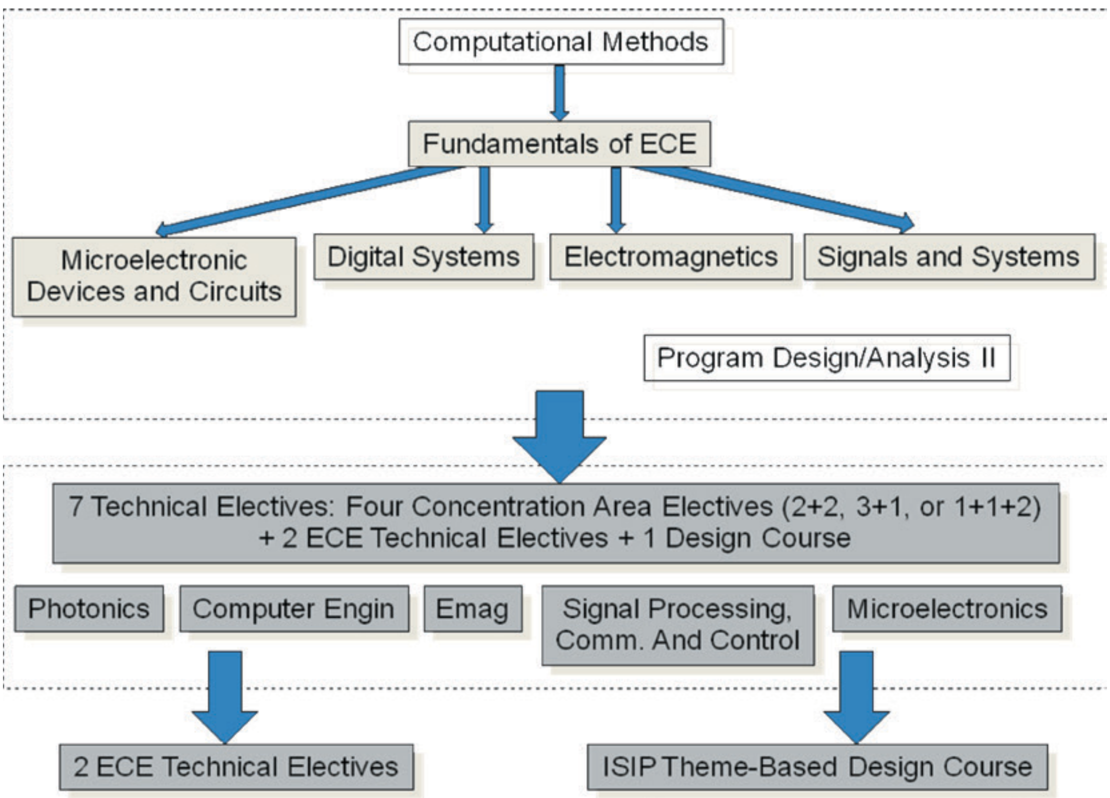


Figure 2. New ECE curriculum resulting from the redesign.

prerequisite content for *Introduction to Electronics: Integrated Circuits*. Concurrently, students took various combinations of *Signals and Systems* (which included a minor lab experience-building an Elenco AM radio kit), *Digital Logic* (which included a well-integrated lab) and *Electromagnetic Fields* (no lab).

In the new core curriculum, the first course, *Fundamentals of ECE*, provides a rigorous, yet broad introduction to ECE providing students with a holistic view of ECE by introducing concepts spanning how to interface sensors and systems with the physical world, how to transfer/transmit energy/information, and how to extract, analyze and interpret information. A roadmap for the remainder of the curriculum and a spring-board launching students into four follow-on core courses (Microelectronic Circuits and Devices, Logic and Computer Architecture, Electromagnetic Fields, Signals and Systems) is provided by introducing these concepts in the context of an ISIP theme-based *Integrated Design Challenge* (IDC). Each semester the theme of the Integrated Design Challenge is changed. Examples of themes, which are intended to provide a meaningful context with connections to students' everyday lives at Duke, include: Smart Home, Duke Real World, Duke Clue, Alice in Wonderland, Star Wars, and Mission Possible. Details of *Fundamentals of ECE* have been presented in [5]. One consequence of rebalancing the core curriculum is the reduction of circuit-centric content.

The five new core courses are followed by seven ECE technical electives that include four ECE Concentration Courses and one culminating Design Course. The ECE Concentration Course selection must ensure breadth and depth while preserving maximum flexibility. This is achieved by requiring at least two of the four courses to be in the same Area and courses from at least two Areas must be taken.

The deconstruction process of the previous core curriculum (see Figure 1) utilized a core curriculum faculty committee with representatives from each Faculty Group to examine and scrutinize the content of all core courses to identify unnecessary redundancy and legacy material as well as to suggest ways to streamline and vertically integrate content from the *Fundamentals* course to the four follow-on courses while keeping in mind; 1) the goal of threading the ISIP theme through all courses, 2) the goal of developing project-based learning experiences with open-ended design, 3) the goal of developing essential skills for effective teamwork. In some cases there were disparities among the faculty regarding the elimination of "legacy material." For example, the topic of Thevenin and Norton equivalent circuits was eliminated from the *Fundamentals* course, and some faculty felt strongly opposed to this decision. Hard decisions had to be made, and in this case it was determined that the proposed topical coverage in the new *Fundamentals* course was more important than Thevenin and Norton equivalent circuits. Pictures of students working on elements of Fundamentals may be viewed at

http://advances.asee.org/vol02/issue04/media/05-media01.ppt

From a Two-Course Sequence in Devices and Circuits to a single course *Microelectronic Devices and Circuits*

The core course *Introduction to Microelectronic Devices and Circuits* is a hands-on, laboratory-centered, vertically integrated introduction to microelectronic devices, sensors, and integrated circuits. In the redesign of this area of study, several considerations were taken into account. On one hand, the class coverage had to provide undergraduate students, who would pursue their non-core courses in areas other than electronics, with a full and practical coverage of the field. On the other hand, the class approach had to generate great enthusiasm in students to pursue their concentration courses in the areas of semiconductor devices, integrated circuits, and VLSI systems. Satisfying these requirements was achieved by redesigning this course into a vertically integrated introduction to microelectronic materials, devices, and circuits. These goals are achieved within a hands-on learning experience in the analysis, simulation, design, and characterization of devices and circuits using an experience that mimics an industrial setting.

The goals of this course are to gain knowledge and experience in the operation and electrical characterization of devices, sensors, and integrated circuits; to experience the design of analog and digital circuits; to experience the techniques and methodologies of circuit analysis, design, assembly, testing, characterization, simulation, and optimization; to gain teamwork experience in project design, analysis, experimentation, planning, documentation, and execution; to develop and increase the student awareness of project budget and time management in reaching pre-planned milestones and deliverables; and to increase the students awareness of engineering ethics in the course of the development, design, and prototyping of their project.

The initial emphasis on laboratory activities is on the electrical characterization of electronic devices and circuits; device characterization and parameter extraction; sensor characterization and parameter extraction; analog-circuit characterization; and digital-circuit characterization. The theme of the project in this class is selected by the instructor. For example, an electronic clock was the theme of the first offering of this class. Students were provided with circuits to implement the most basic form of an electronic clock. This prepared design is intended as a confidence-builder for students who have no prior practical experience in assembling a circuit, debugging it, and making it work. This portion of the project was brief, typically lasting two weeks. The project is then declared open-ended until the end of the semester, and students are asked to design an electronic system, based on the basic project, by designing, implementing, and simulating any additional features to it that they choose. This open-ended part of the project introduces the students to the process of design, to the skills needed in making circuits work, and in the experience in simulating such circuits. One requirement added to the open-ended part of the project is the use of a sensor, which aligns the course project with the ISIP theme. The students are then faced with the challenges of integrating digital and analog circuits, and developing skills in the use of analog-to-digital and digital-to-analog circuits. Emphasis is placed on estimating power consumption in the designs.

Throughout the semester and especially during the project part of the class, two to three students form a company to which they give a name and design its logo. Every student is expected to have an engineering notebook, i.e., a notebook with stitched binding. Students develop an understanding that their engineering notebooks are legal documents in the real world. It must be signed and witnessed by trust-worthy co-workers/colleagues who understand the work. Entries in engineering notebooks must be in permanent ink, not pencil. Each page must be numbered and have the title and number of the project. All data must be recorded directly into the notebooks, including all possible details. Engineering notebooks are the technical diary of ideas, the alternatives considered, the decisions reached, interactions with other people and organizations, changes made along the way, sources of all information, and the implementation of project flow.

After the initial design of the open-ended part of the project, each company writes a brief block-diagram report describing their system, a brief venture capital proposal that includes their tentative budget, and a final project report. The venture-capital proposal is funded to a maximum level of $50 per student. Subsequent offerings of this class have included projects based on designing a two-way, infra-red or RF, remote-control circuit that initiates a remote process and displays its result. The remote process must be sensor-based. Examples of projects ranged from remote sensing of humidity in plant soil to the remote sensing of wind speed at the top of buildings. For a short video example of a student demonstrating an infrared transmission soil moisture system designed in this course, please see:

http://advances.asee.org/vol02/issue04/media/05-media01.cfm

From Digital Logic to *Digital Systems* (including Computer Architecture)

In reforming the course sequence in *Digital Systems*, there were several boundary conditions. Whereas there had been two required courses in the general area of computer engineering in the past curriculum (*Introduction to Logic Design*, and *Introduction to Computer Architecture*), there would be a single required course in the new curriculum (*Introduction to Digital Systems*), with the architecture course becoming an elective for those with greater interest in the field. There was also increasing demand for senior design project opportunities in computer engineering broadly, and our introductory courses had to prepare students well for this. Though the existing introductory logic design class had the great advantage of already having a laboratory well integrated with the lecture material, there was desire to increase the sophistication and realism of course projects. The old course covered combinational and sequential logic design more or less exclusively, stopping short of a clear treatment of digital computers. With just a single required course, it became a priority to weave a basic treatment of computer organization and design into the first course. The old course also introduced students to hardware description language (HDL) design techniques, but did not do so in sufficient depth to make students proficient in HDL methods; course designs were largely manual and thus both greatly limited in complexity and out of step with industry practice. In reviewing comparable courses at peer institutions, it was clear that the pace of our course was somewhat slow. The existing computer architecture course was considered to be in good shape, though under constant pressure to expand coverage due to advances in the field; it would clearly benefit from students coming to the table with a basic understanding of digital computation.

In the revised *Introduction to Digital System*s course, by increasing the pace substantially through the classical material on combinational and sequential logic circuits, time was freed up to expand coverage of HDL design techniques (using VHDL in our case) and to add a substantive treatment of basic computer organization, as well as a number of advanced topics skipped in the previous course. The computer organization unit takes students through the register-level design of a simple single-accumulator ALU, delves into the details of the design of the control unit for this simple machine, and introduces assembly language programming. The gradual introduction of VHDL design techniques throughout the semester allowed the sophistication of the prescribed weekly lab assignments to be increased. A lab introducing practical aspects of analog-to-digital and digital-to-analog conversion was added to relate the course more strongly to the Integrated Sensing and Information Processing theme. Although it was not part of the original plan, it became clear during the initial offering of the revised course that students were advancing so quickly in the lab that a final design project was feasible, and they were eager for a more open-ended, team design experience. The importance of including a final project was validated when the instructor in the first beta-test offering of the new course observed that projects being completed by that class of freshmen and sophomores were comparable to the projects being completed by seniors in the senior digital systems design course that year from the previous curriculum.

The ability of underclass students to readily program an FPGA or other programmable logic device to handle the details of a finite state machine with many dozens of states combined with the existence of cheap prototyping boards and inexpensive (often free with a textbook) but powerful CAD tools is the winning combination that allows freshmen and sophomores to feel the pride of personally designing and implementing a “real” digital system. Our practice has evolved to giving students a list of possible (and now feasible) projects to choose from each semester, but always with the option of students proposing their own project idea. The allure of designing their own state-machine-based games or other devices using a sea of simple LEDs and switches, works wonders to spur students’ creativity.

This very positive experience with the motivating power of team design project work in this and several of the other new core courses, combined with the increased skill set students brought out of these core courses into their later elective and design courses, strongly informed our reworking of the senior design courses in the computer engineering area. The existing "Advanced Digital Logic Design" course, whose senior projects were being upstaged by the work of the underclassmen, was significantly reworked with greatly increased expectations as to the scope and complexity of the expected product, leveraging students' competence in intermediate VHDL on arrival in the course. The revised version of that course requires teams of students to implement a simple but fully standards-compliant Ethernet switch with FPGA technology. This course is fully accessible to students who have taken only the introductory digital systems class. An additional senior design course option was created by morphing an existing embedded systems course, which had been a pure elective featuring an extensive solo design project, into an "official" senior design course, with group projects supplanting the solo efforts, and greater attention paid to the process of managing the design project. This revised embedded systems course has proven to be extremely popular, even though it has a deeper prerequisite chain (requiring both the introductory digital systems course and the computer architecture course), and the project demo day for the course has become a highlight of the annual computer engineering calendar. Examples of student project work is available at http://advances.asee.org/vol02/issue04/media/05-media02.ppt

Electromagnetic Fields with a New Laboratory and Antenna Content

Electromagnetic Fields is viewed in many ECE departments as a "difficult" course for the students and a difficult course to teach by the faculty because of the necessary emphasis on physics and mathematics, such as vector calculus and partial differential equations. Furthermore, it is difficult for students to develop an understanding of the physical meaning of vector calculus operations such as divergence, curl and gradient. Students develop an ability to "turn the handle" on the mathematics, but often lack an intuitive understanding of these concepts. As a consequence, the course often develops a reputation as being abstract and difficult, and some students postpone taking the course until they are seniors. In updating this course we were faced with the challenges of adding material to better engage the students and to connect to the ISIP theme without adding so much material that the course becomes too time-consuming. The result was two primary changes. First, we reoriented the basic curriculum to emphasize practical elements that connect course content to the integrated sensing theme, such as antenna design and measurement, and abbreviated some elements that did not connect as well, such as the solution of Laplace's and Poisson's equations. Second, we developed a new laboratory component with the goal of making otherwise abstract material more tangible. That voltage and current vary with position on a transmission line is surprising and counter-intuitive to students with lumped circuit intuition, and that it takes partial differential equations to describe the phenomena makes it difficult to visualize. But a lab in which the students measure this spatial distribution of voltage with an oscilloscope makes the concept less abstract.

The course remains theory intensive, partly due to the nature of the material and partly due to the preferences and experience of the faculty teaching the course. We find, however, that modest labs that are carefully coordinated in time with the course concepts from lecture are favorably commented upon by the students. Our chief concerns in the design of the new laboratory component were not to dramatically increase the required course workload, and to balance the trade-off between exploration and simple procedure-following in the lab.

For a one semester course, we created 5 labs (approximately one every other week) that connect to each of the major components of the course. The labs contain pre-lab work, for example, computing the voltage distribution on a transmission line configuration that they will measure in the lab, but the labs are otherwise designed to be completed in entirety in one 3-hour period. Each combines well-defined, basic lab measurements that attempt to reinforce the theoretical calculations from the lecture side of the class with one application-oriented exploratory task.

In the **transmission line transient** lab, students measure the complex reflection dynamics of pulses and steps in unmatched lines, and they determine the unknown location of a line fault using time domain reflectometry. In the transmission **line steady state** lab, they measure the inhomogeneous voltage and impedance distribution on a transmission line, and they measure the unknown impedance of a simulated antenna and design and implement an appropriate stub matching element. In the **Electrostatic Crosstalk** lab, the students quantify the ever-present capacitive coupling between adjacent traces on a printed circuit board, and they measure the unknown coupling capacitance of several different configurations. In the **electromagnetic waves lab**, the students use a modern commercial simulation software package (COMSOL Multiphysics) to compute radio wave penetration through complex structures not solvable analytically, and they design one such structure to meet a specification on its electromagnetic power shielding. The final lab, **Antennas**, pulls together many of the concepts into one activity in which each group of 3 students designs, constructs, and measures their own 2.4 GHz antenna constructed from a potato chip can (e.g. Pringles). The students design the feed point based on the target operating frequency, measure the frequency dependent input impedance of their antenna to confirm the operating frequency, and lastly measure one plane of the antenna radiation pattern to compare predicted and measured antenna directivity. Examples of students working on lab exercises in Electromagnetic Fields are available at

http://advances.asee.org/vol02/issue04/media/05-media03a.ppt

Signals and Systems before and after the Curriculum Redesign

As is often the case for traditionally-taught introductory signal processing courses, the core course *Introduction to Signals and Systems* had a reputation for being abstract and theoretical. Students often described it as "just another math course." Previous attempts to increase course relevance involved an emphasis on MATLAB applications, such as a correlation project that involved detecting a signal embedded in noise (cf. sonar) and a music synthesis project that involved manipulating signals to recreate the musical notes and sound effects of a familiar piece of music. For the final course project, students constructed an AM radio from a kit with basic components. These changes, which provided new hands-on experiences that complemented the existing strong grounding in signal processing theory, were well-received by the students and had a positive impact on the course.

More recently, our adoption of the ISIP theme has inspired more sweeping changes in *Signals and Systems*. Because even the newly added project exercises had only limited practical components, the primary reform goal was to present course material in a more relevant, real-world context. To achieve this goal, the course now includes a series of theme-driven, hardware-based laboratory exercises. The integration of a hardware-based laboratory into a signal processing course is not unique, although such laboratory experiences are most often found in more advanced courses focused specifically on digital signal processing (DSP) and not in the introductory signal processing course [21,22,23,24,25,26]. Fundamental concepts such as filtering and sampling are commonly addressed in hardware-based laboratory exercises. However, the emphasis is often on the mechanics of the hardware implementation and topics are rarely presented in the context of realistic applications. While such an approach may be ideal for senior-level students, it is not suitable for less-experienced students, as the perceived (or real) technical difficulty of such a course may deter students who do not immediately grasp the relevance of the material [27].

The laboratory hardware (Texas Instruments' TMS320C6713 DSP Starter Kit [DSK]) was selected because it was suitable for both introductory and advanced students. Unlike much DSP hardware which must be programmed using C or Assembly programming languages, the DSK could be programmed using MATLAB and SIMULINK. Since students entered *Signals and Systems* already possessing experience using these programming tools, they were able to focus on signal processing algorithms and not the frustrations of debugging complex code.

In a pedagogical model developed by Wright et al. [27], interactive demonstrations, MATLAB simulations, and real-time DSP programming supplement the theory presented to the students. This pedagogical model has been shown to make DSP more understandable and accessible to a broader range of students [27]. New applications for *Signals and Systems* were built upon this model, with the addition of two innovative features for their exercises: the use of the ISIP theme to introduce real-world problems, and the vertical integration of these applications throughout the signal processing curriculum.

A series of four DSK-based laboratory exercises were developed for *Signals and Systems*. These exercises included Digital Audio Effects, a Dual-Tone Multi-Frequency (DTMF) System, Sampling and Aliasing, and a Voice Scrambler/Descrambler. Although the signal processing component of the ISIP theme was dominant in each exercise, students also were required to integrate one or more sensors or transducers into their system. Each exercise illustrated one or more fundamental concepts in the context of a real-world application. For example, the DTMF encoder/decoder was used to simulate a touch-tone phone system. Thus, the technical aspects of the project were motivated by real-world constraints, providing a platform to discuss topics such as harmonics, signal distortion, and the importance of designing robust systems. In addition, each exercise contained open-ended problems and challenges, rather than prescriptive instructions, to encourage students to think critically about the concepts and their application. Student feedback has indicated that such application-driven exercises enhance the appeal of signal processing without compromising learning of theoretical concepts or precluding more specialized instruction in DSP design and programming [28].

Students who choose to pursue advanced study in signal processing may also take the technical elective *Fundamentals of Digital Signal Processing*. As with *Signals and Systems*, our curriculum reform modified this course to include ISIP-inspired applications. Prior student experience is leveraged by using the same DSP hardware as in *Signals and Systems*, thereby facilitating more challenging and complex laboratory projects. The ISIP theme-based projects include Vowel Recognition (in the context of a simplified voice-activated security system), an Electric Guitar Tuner, and a Heart Rate Monitor. As in *Signals and Systems*, the focus of each project is on the development and implementation of appropriate signal processing algorithms. In addition, in keeping with the ISIP theme, students in *Fundamentals of DSP* must also learn to interface a variety of sensors/transducers with their system. As an example of field data acquisition, students are shown in Figure 3 gathering heart rate data on iPods for further analysis in the signal processing laboratory.

Upper-Level Curriculum Redesign

The goal of redesigning the upper-level ECE courses, including the culminating design courses, was to align their content and structure to fit seamlessly with the core curriculum. The approach taken by each instructor to perform this alignment spanned a wide spectrum. Some instructors chose to create a laboratory experience with an ISIP theme and to integrate the lab content with the lecture content to provide the tight coupling described earlier in the philosophy of the redesign. Other instructors chose to focus on ISIP-themed, in-class examples that illustrate the solution to real-world problems with no formal lab experience. Descriptions of six upper-level technical electives follow

Figure 3. Students in Fundamentals of DSP collect heart rate data to be processed in the laboratory.

that illustrate how the courses were aligned with the redesign philosophy and ISIP theme. Laboratory exercises emphasizing real-world applications have been created and/or linked through time and synchronized with the lecture to provide a cohesive integration of course content. Real-world, ISIP theme-based examples have been crafted to provide connections to current technologies, providing immediate relevance that increases student engagement.

Evolution of *Modern Optics I*

Applications of optics are widespread in everyday life in the modern world. Traditional optical systems like cameras have become ubiquitous, while new applications like data storage (compact disc and digital video discs) and optical communications provide crucial enablers for the information technology that is transforming our culture. One of the Areas of Concentration for the redesigned curriculum at Duke is Photonics. Photonics covers progress in optical sciences and its impact on modern technology. Modern Optics I is the foundation course for the Photonics Area of Concentration, intended for juniors and seniors interested in pursuing in-depth courses related to optics and photonics. The prerequisite for Modern Optics I is *Introduction to Electromagnetic Fields*, as the basic propagation properties of electromagnetic waves are essential in understanding the properties of optical fields. Furthermore, this course was developed with an intention to capture the multidisciplinary character of optics research, with foundations in Physics and expanding applications into biomedical research. Modern Optics I is cross-listed with the Physics department, and draws students from Physics, Chemistry and Biomedical Engineering departments.

This course is designed to convey the fundamental properties of optical phenomena required to understand the operation of basic optical devices and systems. The topics covered include classical optics approaches such as ray optics, electromagnetic optics, interference, optical resonators and polarization, as well as the quantum nature of light that enables modern day devices such as lasers and photodetectors. The foundational knowledge is applied to the understanding of optical devices like interferometers, spectrometers and lasers that find applications in various aspects of ISIP theme, such as imaging, sensing, communication and display of information. Figure 4 shows the designed structure of Modern Optics I in the context of the Photonics Area of Concentration courses in the ECE Department.

The course employs an integrative instructional approach that combines lectures and laboratory exercises carried out in a team environment. The laboratory exercises are coordinated with the contents of the lecture, and provide students with hands-on experience in the construction and comprehension of basic optical systems including simple imaging systems, propagation of Gaussian beams, spectrometers, interferometers, holography, lasers and optical fiber communication.

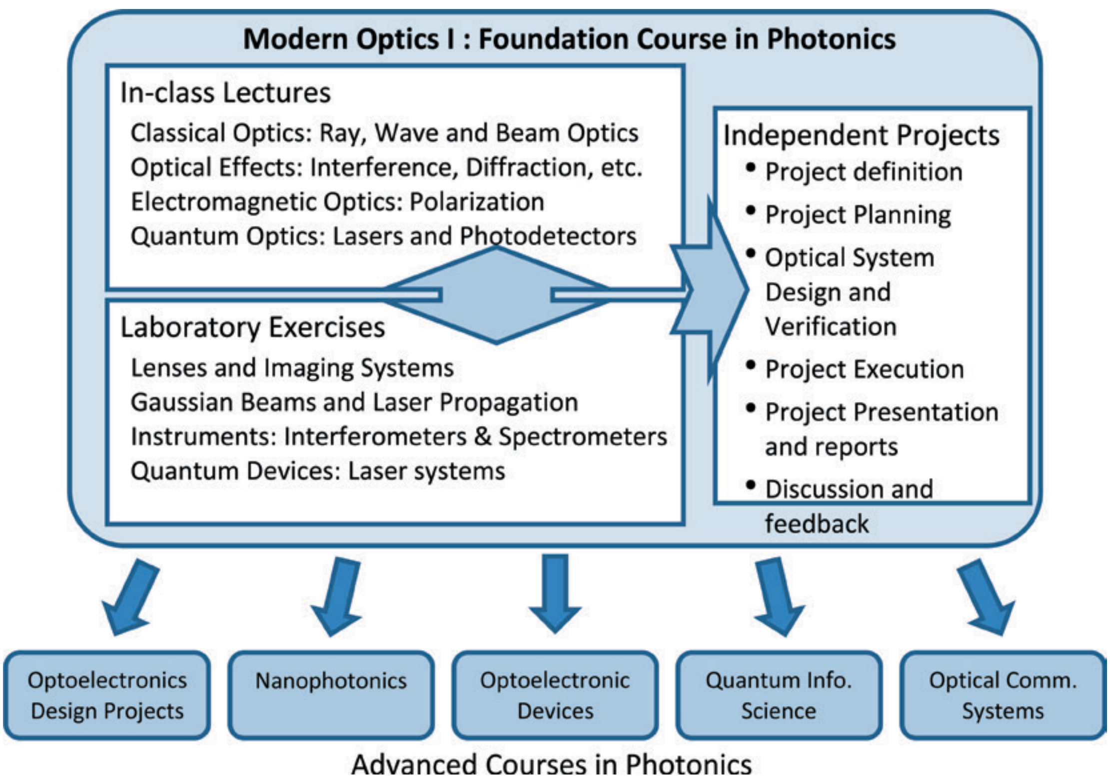


Figure 4. Structure of Photonics Area of Concentration courses and role of Modern Optics I.

The initial set of laboratory experiments have been established and implemented, and more experimental topics are constantly under development to form a library of lab exercises. While a defined set of core lab exercises will be carried out to guarantee consistency of the course year after year, each instructor will be able to offer some variation of advanced laboratory topics to reflect a shift in emphasis and as the field of optics and photonics evolves. In the first revised implementation of this course, the student teams were asked to identify a laboratory project by the middle of the semester, which they will work on for the final 4 weeks of the course. Each team proposed their project topic and met with the instructor to discuss their plans, identify the objectives, and make a request for the equipment necessary to complete the project. Each project had to comprise a complete optical system that included an optical source and a detector, and had to take advantage of a novel optical interaction with a component or sample to provide a unique ISIP related function. Examples of projects that were demonstrated in the course included novel imaging systems, low-coherence inteferometric imaging systems using optical coherence tomography, and external-cavity stabilized diode lasers. Examples of students working on photonics lab exercises may be viewed at

http://advances.asee.org/vol02/issue04/media/05-media03.ppt

***Linear Control Systems* with New ISIP Theme-Based Lab**

Linear Control Systems is an elective course that may be taken either as an ECE Concentration Elective in the Signal Processing, Communications, and Controls Area or as an ECE Elective. The course focuses on single-input, single output systems that are placed in either open or closed loop control patterns. By the end of the course, students are expected to (1) identify components of electrical, mechanical, and electromechanical control systems, (2) model electrical, mechanical, and electromechanical systems with control in the time domain and in the frequency domain, and (3) design linear control systems for electrical, mechanical, and electromechanical systems in the time domain and the frequency domain.

Through the pre-requisite chain, students must have completed Fundamentals of ECE, Computational Methods in Engineering, and Signals and Systems. Students are expected to design, conduct, and analyze electronic experiments using fundamental laboratory equipment (breadboard, resistors, amplifiers, etc.) and computational tools (e.g. MATLAB and data acquisition hardware). In 2005, the Linear Control Systems class had no hands-on laboratory component and no tangible link to the departmental theme of Integrated Sensing and Information Processing. When asked, “What changes should be made to this course and why?” examples of student replies included:

- “I would like to see more of a physical component to this course, such as bringing in examples of control systems we are studying.”

- "I would have liked some hands-on experience with control systems. It would be interesting to have a system and be asked to change its design to meet specific parameters. This would require the addition of a lab portion of the course."
- "Some sort of hands on element would be a positive change to the class…"

As a part of the curriculum redesign, and because of the opportunities presented by the skills gained through the new core curriculum, this course has changed in several significant ways. A three-hour, weekly laboratory session was created. Students now take examinations in the laboratory. This allows them access to the computational tools discussed in the course and the instructor can now require that students demonstrate more comprehensive abilities due to the extra time and data acquisition equipment available

Before the curriculum redesign, only very basic computational problems were given. There were two major impediments to assigning deeper and broader computational assignments: the lack of a single standard computational platform and the lack of a period of instruction for teaching the tools. Requiring that all students take Computational Methods solved the first problem, as all students taking Linear Control Systems must now have had both an introduction to MATLAB. Adding a laboratory solved the second impediment. Students now conduct hands-on experiments with control systems. Before the curriculum redesign, there was no laboratory experience for this course. All knowledge of and experience with control systems was theoretical. Now, however, to strengthen the connection to sensing and information processing as well as to enhance the students' facility with control systems, students analyze and design electric circuits and use computational tools to compare physical measurement results with theory.

With respect to student satisfaction, students fill out a course-specific end-of-year evaluation, and the question - "How well has this course taught you to design linear control systems for electrical, mechanical, and electromechanical systems in the time domain and the frequency domain?" - has seen large improvement from the offerings before making the above changes to the present time. For the two years prior to adding hands-on experiences, the average (on a scale from 1 to 7 with 1 being "very poorly" and 7 being "very well") was a 6.05 in 2005 and 6.21 in 2006. The scores went up to 6.38 in 2007 and 6.56 in 2008. For examples of student work in Linear Control Systems, please see

http://advances.asee.org/vol02/issue04/media/05-media04.ppt

Image and Multidimensional Signal Processing

At Duke University, researchers are currently struggling with a wide variety of problems in multidimensional signal processing and face challenges of limited storage space for massive data sets, limited processing power, and partially or poorly understood physical processes underlying the data collection. Duke engineering undergraduates are very likely to encounter these or similar issues at some point in their futures; the course described here, ***"Image and Multidimensional Signal Processing,"*** addresses these information processing problems in a framework formerly unavailable to Duke undergraduates. The course introduces students (primarily juniors and seniors) to the theory and methods of digital image and video sampling, denoising, compression, reconstruction, stenography, and analysis. This course is an advanced signal processing course available to students after they complete Signals and Systems, one of the linchpins of the new curriculum. The material in Image and Multidimensional Signal Processing begins with a foundation of the two-dimensional Fourier transform, which builds directly on concepts covered in Signals and Systems, and then expands upon those concepts to cover sampling, discrete Fourier transforms, alternative basis representations of images, and a variety of reconstruction methods for removing noise and distortions from digital images. The objective of this course is to develop the following core skills in students:

- Ability to apply mathematical, scientific, and engineering principles to image filtering, denoising, and reconstruction.
- Ability to program image filtering, denoising, and reconstruction methods in MATLAB.
- Ability to communicate effectively in both writing and speaking in a variety of contexts.
- Ability to function effectively on long-term project teams.

A recurring theme throughout the course is "Integrated Sensing and Processing." Specifically, we strive to address key underlying questions such as the following: "Given a data collection model, is the proposed processing technique optimal? How can its performance be characterized? Could an alternative mode of data collection yield higher performance?"

The instruction in the course is balanced between a focus on theoretical principles and project-based learning. Each lecture begins with a theoretical investigation of some tool or technique. We discuss the context in which that tool could be useful, how it can be derived from first principles, and its advantages and disadvantages. Students are provided with lecture notes that are missing key insights or mathematical derivations, which we then fill in together as a group; this method greatly enhances class participation. The second half of each lecture is devoted to demonstrations in MATLAB of how the theoretical concepts can be translated into practical algorithms. Homework is structured similarly; several questions revolve around understanding underlying theoretical concepts, followed by a mini-project students must complete in MATLAB.

A key component of the course is the completion of group projects, and the project component of the course and the theme of "Integrated Sensing and Processing" are closely interrelated. For example, in a computed tomography (CT) volume segmentation project, students used tools learned in the class to process data sensed by a CT scanner. That processed data could then be used by the original researchers studying pediatric cartilage development to guide future sensing efforts with minimal risk of missing important features. Another student group studied novel designs of spectral imagers, which allowed indirect measurements of spectral images to be collected and resulted in a challenging inverse problem. By studying the inverse problem solution and the quality of the reconstructed spectral images, students tried to quantitatively assess the impact of the novel sensing approach integrated with image processing techniques compared with more conventional sensing systems. In third student project, a team studied the emerging framework of "compressed sensing", which deals with reconstructing large images or other signals from a limited number of indirect measurements. This allows the students to examine the tradeoff between sensing resources such as detector array area and processing issues such as computation time and noise sensitivity. For examples of student image and multidimensional signal processing project results, see

http://advances.asee.org/vol02/issue04/media/05-media05.ppt

Computer Network Architecture*, and *Wireless Networking and Mobile Computing

Computer Network Architecture, and *Wireless Networking and Mobile Computing*, are two courses in the Computer Engineering Area of Concentration. Highlighting this particular pair of courses exemplifies building sequential, vertically integrated ISIP theme-based, upper-level courses. Computer Network Architecture introduces students to basic concepts of computer networking. The layered architecture of the network protocol stack is the focus of discussion, with the Internet as the overarching example. The course begins with a high level view of networks, with frequent historical references to the state of the world before networks existed. Students begin to appreciate the networking services they take for granted today, and become more inquisitive about "how it all came about". The instructor blends the historical perspectives and anecdotes with technical material, and gradually slides to the pure technical content of the course. At this point, students find themselves with a satisfactory answer to the question "why am I taking this course?" This is an important objective of the course – to make students naturally interested, as opposed to a required step towards graduation.

The course's technical content begins with the application layer of the protocol stack. Technologies underlying Internet services and applications (that students use on a regular basis) are analyzed and explained. For example, the components of the Email application are discussed with specific references to IMAP and POP protocols. HTTP, FTP, DNS, Peer-to-Peer networks, and other topics covered, with references to software tools that students use on a regular basis. Since students are familiar with these tools, they quickly relate to the course material, and often have very insightful questions. It is at this point the course introduces network programming concepts and lab assignments. The assignments are motivated as a stepping stone towards building one's own networking software, with all the features that they would ideally like to have. Students are asked to build their own instant messaging (IM) software, and use it as a custom system for future messaging with their friends. This excites most of them because they begin to build systems that they have only used in the past. Their engagement to the course stays high. More importantly, they learn to apply their theoretical knowledge into building practical, working systems.

The course then moves onto the transport layer, with the Internet TCP protocol as the case study. The concepts become harder at this stage, and the instructor uses range of real life parallels to help with grasping the ideas. Questions are posed from real life, and when students answer them using common sense, their answers are steered to the context of networks to show the networking equivalent. This form of analogy-based learning helps in grasping the core idea.

The course continues to cover computer network routing with reference to the IP protocol. The link and physical layer follows after routing, with more assignments apply the concepts across different layers. The instructor raises a variety of questions that were not covered in this course, and when students are eager to learn the answer, the instructor invites them to the follow up course — Wireless Networking and Mobile Computing. This is like an interest "hook" or "teaser" to draw students into the next level of computer networking.

Wireless Networking and Mobile Computing is a course that was created in spring 2007. This course is designed to introduce senior undergraduate and graduate level students to the theory, design, and implementation of wireless/mobile networks. The course requires an undergraduate level networking background equivalent to *Computer Network Architecture* previously discussed. The instructor spends the first three classes on a primer of *Computer Network Architecture*, emphasizing the approximately 15 key concepts that one must understand very well. The primer serves multiple objectives. Students from different backgrounds have a chance to "fill gaps" in their understanding of certain concepts.

The primer also serves as a gateway to the principal content of the course. The instructor discusses the background concepts on wired networking (e.g., the Internet), but follows this with questions on how such networks can be extended to a wireless medium. Classes are intentionally ended with these open-ended questions — an attempt to prepare students for the principal course content. Many students recognize how their existing knowledge of computer networks is limited, and that this course is an opportunity to extend that knowledge. At this point, the instructor introduces the fundamentals of wireless communications and networking. Concepts are posed as research problems, and students are encouraged to use their existing understanding to solve them. Questions are of the form "In a wired network, the transmitter performs collision detection, however, that is not feasible in wireless . . . so what do you do?" Students collaboratively formulate a solution, often diverging from the correct one. The instructor allows such divergence, sometimes even encouraging them down the divergent thread of analysis. Most often, the students themselves realize the mistakes they have made, and perform the necessary backtrack.

When students are unable to self-correct, the instructor points the error in reasoning, and restarts the discussion. This is the essence of inquiry-based learning – placing students in situations where they must grapple with their own misconceptions, taking on the responsibility for their own learning, as the instructor fuels the learning process by pointing out the discrepancies between the student's explanation and evidence. The first 6-7 classes are devoted to this process, dwelling on the foundations rather than lecturing on research content. Where appropriate, students are steered by the instructor to classical papers in the literature that addresses the content necessary to answer the students' questions. The rest of the course builds on the thorough understanding of the wireless channel.

The subsequent content in the course is provided through research papers from high quality conferences and journals. Students are expected to write critiques of research papers as assignments for every class. The research papers are discussed in class, and the instructor draws from broader/peripheral topics that are relevant to the context. The course starts with the wireless Physical layer and moves on to the MAC layer. Channel access protocols and scheduling algorithms are studied in detail, with emphasis on smart antennas, multi-channel protocols, power control, rate control, and carrier sensing. Real life analogs are used wherever feasible, and students are strongly encouraged to challenge the ideas presented to them.

This wireless networking course requires students to complete a research project. Students must identify a new problem, formulate it carefully, design the solution, evaluate it on a simulator or test bed, and present the results in the form of a term paper. As students begin to think independently and review papers critically, they are asked to submit project proposals. The instructor advises them to think of multiple ideas before finalizing on one for their projects. As a result, students typically end up with a topic that excites them the most. The software/hardware infrastructure is provided for executing the projects. Students work in groups of 2 or 3. The advisor points them to a wide range of topical papers; students contact the authors of the papers at other universities to clarify uncertainties. The overall exercise prepares them not only academically, but also towards effective project management. The course culminates with a final project competition sponsored by Cisco. This project is called the Cisco Research Contest, and the top 2 or 3 projects are awarded the Cisco Champions Award. Duke faculty and senior researchers from Cisco judge the contest. Each group makes a presentation and presents a demo of their project, and answers questions from the judges and other members of the audience. Students enjoy learning about other projects and are reassured by the industry's participation in the event. Examples of projects and students receiving the Cisco Champions Award are available at http://advances.asee.org/vol02/issue04/media/05-media06a.ppt Several Ph.D. students often develop apprehensions about the practicality of their research, and this industry-university event helps boost their motivation. Moreover, growing industry participation is likely to attract undergraduates to graduate school – a critical need in the face of dropping enrollments.

Optoelectronics Design Projects **before and after the Curriculum Redesign**

Engineering educational experiences optimally culminate in a hands-on experience that incorporates design, construction of the designed system, and testing or operation of the system. Designing a system to a standard also helps to give students an understanding of the broader context of their work in the technical domain of the system. Additional design considerations that are particularly pertinent today include power consumption and materials utilized, and how this affects the environment.

The course "*Optoelectronics Design Projects*," is one of several senior-level design courses that was redesigned to provide a culminating design/build/operate experience for engineering students in ECE, BME, and CEE. The course has been taught for over 10 years as a team-taught course by Professors Brooke and Jokerst, whose specializations are in circuit design, wireless communications circuits, optical design, optoelectronic devices, and sensing. The course content, as taught in Fall, 2009, focused on the design, construction, and operation of a colorimetry sensor system for water quality testing that was connected to a base computer using an IEEE Standard Zigbee wireless interface. This project fits well with the ISIP theme, and integrates student knowledge in the areas of circuits, wireless communication, optics, optoelectronic devices, mechanical optical and electrical design, soldering, and optical and electronic testing.

Students are assigned to groups of 4 students, and the groups are established as competitive small companies bringing their new product to market. Resource management is emphasized through GANTT charts, leadership, teamwork, and group management discussions. A "skills inventory" designed by Professors Brooke and Jokerst in the days leading up to, and into the second day, of classes gives the instructors the information needed to distribute the skill sets needed across the groups of students. Skill sets that are inventoried include optics, circuit design, wireless communications, computer programming, soldering, working in a group, and leadership. Both classroom and life experiences (e.g. internships, summer jobs) are included in the inventory.

Just in time lecture materials are used in the first half of the semester to acquaint the students with the essential knowledge necessary to address the project. Each team has access to the knowledge of the prior teams (from the previous semester, on websites), and to the "gurus" (Professors) when they have questions. Each Thursday lecture period is devoted to a "report to management" (oral to the entire class) from each team. Individual grades for each student are based upon these oral reports (2 per student) and on the single test given near mid-term. Two written group reports are graded, and each group member receives the common report grade. The weekly oral reports are useful in that the groups are able to observe and evaluate the progress of other groups, and healthy competition, and collaboration, ensues.

The project goals and expectations are clearly outlined on the first day of class, and optional additional project goals are also given, should the students complete the basic project goals before the end of the semester. Time to market (which group successfully tests their project first) and project performance (e.g. power dissipation) are also used for final project assessment. Examples of students working on opto-electronics design projects may be viewed at

http://advances.asee.org/vol02/issue04/media/05-media06.ppt

It should be noted that although we have highlighted the Opto-Electronics Design Course to illustrate the process of aligning a course with the ISIP theme, all of the other Design Courses have also undergone similar reform.

ASSESSMENT

Two primary goals of the curriculum redesign were to increase student's ability to design a system or component to meet a set of constraints and to work effectively in teams. The following data analyses address the effectiveness that the redesign has met these goals from the students' perspective. Following that analysis, course and laboratory grades are examined before and after the curriculum reform, and the results are discussed.

End-of-Course Instructor/Course Evaluations by the Students

For the student reported data a total of 1,260 student responses were analyzed from two questions from a 35 question, school-wide, course/instructor end-of-course evaluation. The instrument may be examined at

http://advances.asee.org/vol02/issue04/media/05-media07.pdf and utilizes a Likert scale from 1–5 where 1 corresponds to *strongly disagree*; 2 corresponds to *disagree*; 3 corresponds to *neutral*; 4 corresponds to *agree*; and 5 corresponds to *strongly agree*. The two research questions addressed by the two tables below are: 1) What impact has the curriculum reform had on the students' perception of their ability to design a system, component or process to meet a desired need and 2) What impact has the curriculum reform had on students' perception of their ability to work on a team.

The data was obtained over the period Fall 2003 – Spring 2006 for the "before" values and the period Fall 2006 – Spring 2009 for the "after" values. All data comparisons except for *Fundamentals of ECE* include multiple instructors. The *Fundamentals of ECE* data utilized values for only a single instructor to eliminate instructor as a factor. The number of student responses (N) is provided for each sample group along with the sample mean, standard deviation and resulting one-tailed p-value with the exception of *Digital Image and Multidimensional Signal Processing* and *Wireless Networking and Mobile Computing* since these two courses were created specifically for the new curriculum. Hence, only the mean, standard deviation and sample values are presented for these two courses. The one-tailed p-values were computed since the underlying question is, "Did the curriculum redesign cause a significant change in the mean value of the student response?" In every core course the results are highly significant. These results indicate that students perceive significant improvement in their ability to design a component or system across the entire core curriculum. For the upper-level courses, Computer Networks and DSP each have significantly positive results with p-values well below 0.05, a typical threshold of significance in t-tests. Control Systems' p-value is 7×10^{-2}, which does not tell the whole story. The average went from 4.5 to 4.7, values that are at the top of the departmental ratings (recall that the maximum response value is 5). Hence, the "before" ratings already indicate strong student self-assessed ability to design. Results for *Modern Optics I* indicate that the course is not selected by many students (low N values), and the lab experience is not valued nearly as much as it is for other courses. Hence, this is a clear indication that the Photonics Faculty Group should consider ways to improve the course. It would be premature to draw conclusions about either the Wireless Networking course or the Multidimensional Signal Processing course, except that the mean value of 4.3 for the Wireless Networking course is in the high end of the departmental scale. Interestingly, the results for our two most popular culminating design courses (Opto-Electronics Design Projects and Digital Systems Design), show that the improvement in the Opto- Electronics Design Projects is highly significant while the change in mean responses for the Digital Design course is negligible. This is another case where the average student response was already at the top of the rating scale. Table 2 presents the statistical analysis results for question 28 of the end-of course-evaluation. In this question students rate how well the course improved their ability to function on a team. The *Fundamentals*, *Microelectronics* and *Digital Systems* courses all produced highly significant results with the most significant result indicated by *Microelectronics*. The *Microelectronics* course experienced the greatest change resulting from the curriculum redesign as described in Section 3. One of the major changes in *Microelectronics* was a pedagogical shift of the learning focus from the instructor to the student. Student inquiry drives the course. As described in Section 3, the Microelectronics course is centered on the ISIP theme-based lab project. Student valuation of this team-based learning experience is evidenced by the mean value change from 2.7 to 4.5 and extremely small p-value of 4.2×10^{-37}. Results for the technical electives all evidence significant improvement in student perception of their ability to function on a team with the exception of Modern Optics I, which shows only marginal improvement. Our two most popular design courses (Opto-Electronic Design Projects and Digital Systems Design) are now both indicating very high ratings in team work ability as rated by the students.

ECE Core Courses (Q27)

Statistical Analysis Results for: ***This course increased my ability to design a system, component, or process to meet desired needs.***

Comparison	N (before)	N (after)	Mean (before)	Mean (after)	Std Dev (before)	Std Dev (after)	P-value
Electric Circuits vs. Fundamentals	58	108	3.5	4.5	0.8	0.7	5.7×10^{-12}
Devices vs. Microelectronics	60	84	3.0	4.4	1.3	0.6	1.6×10^{-11}
Digital Logic vs. Digital Systems	71	143	3.6	4.4	0.9	0.8	9.5×10^{-9}
Electromagnetic Fields (before) vs. (after)	75	101	2.4	3.2	1.4	1.2	3.0×10^{-5}
Signals & Systems (before) vs. (after)	86	97	3.6	4.1	1.1	0.8	2.1×10^{-4}

ECE Technical Electives
(selected from many technical electives)

Statistical Analysis Results for: ***This course increased my ability to design a system, component, or process to meet desired needs.***

Comparison	N (before)	N (after)	Mean (before)	Mean (after)	Std Dev (before)	Std Dev (after)	P-value
Modern Optics I (before) vs. (after)	12	9	2.9	3.0	1.5	1.5	0.45
Controls (before) vs. (after)	77	31	4.5	4.7	0.8	0.8	7.0×10^{-2}
Digital Signal Processing (before) vs. (after)	46	34	4.1	4.7	1.1	0.7	1.3×10^{-3}
Computer Networks (before) vs. (after)	23	24	2.2	3.8	1.1	1.1	1.3×10^{-5}
Digital Image and Multidimensional Processing (after only)		31		3.9		1.2	
Wireless Networking & Mobile Computing (after only)		35		4.3		0.7	

ECE Design Courses

Statistical Analysis Results for: ***This course increased my ability to design a system, component, or process to meet desired needs.***

Comparison	N (before)	N (after)	Mean (before)	Mean (after)	Std Dev (before)	Std Dev (after)	P-value
Opto-Electronic Design Projects (before) vs. (after)	35	38	2.4	4.6	1.4	0.6	3.2×10^{-11}
Digital System Design (before) vs. (after)	30	17	4.7	4.6	0.5	0.8	0.23

Table 1. Statistical analysis results for question 27 of the Pratt end-of-course evaluation asking students to self-rate their ability to design a system, component or process.

ECE Core Courses (Q28)

Statistical Analysis Results for: *This course increased my ability to function on a team.*

Comparison	N (before)	N (after)	Mean (before)	Mean (after)	Std Dev (before)	Std Dev (after)	P-value
Electric Circuits vs. Fundamentals	58	108	3.4	4.3	1.2	0.9	2.2×10^{-6}
Devices vs. Microelectronics	60	84	2.7	4.5	1.3	0.8	4.2×10^{-37}
Digital Logic vs. Digital Systems	71	143	3.8	4.2	1.2	0.9	7.2×10^{-3}
Electromagnetic Fields (before) vs. (after)	75	101	2.8	2.9	1.4	1.3	0.23
Signals & Systems (before) vs. (after)	86	97	3.7	3.6	1.2	1.1	0.41

ECE Technical Electives
(selected from many technical electives)

Statistical Analysis Results for: ***This course increased my ability to function on a team.***

Comparison	N (before)	N (after)	Mean (before)	Mean (after)	Std Dev (before)	Std Dev (after)	P-value
Modern Optics I (before) vs. (after)	12	9	2.7	3.4	1.4	1.4	6.9×10^{-2}
Controls (before) vs. (after)	77	31	2.8	3.7	1.4	1.1	4.4×10^{-4}
Digital Signal Processing (before) vs. (after)	46	34	3.8	4.2	0.9	0.8	2.6×10^{-2}
Computer Networks (before) vs. (after)	23	24	2.2	3.2	1.1	1.4	6.2×10^{-3}
Digital Image and Multidimensional Processing (after only)		31		3.8		1.1	
Wireless Networking & Mobile Computing (after only)		35		4.1		0.8	

ECE Design Courses

Statistical Analysis Results for: ***This course increased my ability to function on a team.***

Comparison	N (before)	N (after)	Mean (before)	Mean (after)	Std Dev (before)	Std Dev (after)	P-value
Opto-Electronic Design Projects (before) vs. (after)	35	38	2.4	4.7	1.4	0.5	2.6×10^{-11}
Digital System Design (before) vs. (after)	30	17	4.5	4.6	0.7	1.1	0.35

Table 2. Statistical analysis results for question 28 of the Pratt end-of-course evaluation asking students to self-rate their ability to function on a team.

Course and Laboratory Grades for the ECE Core Courses Before and After the Reform

Table 3 presents laboratory grades averaged for the period 2004–2005 and 2008–2009, which is clearly before and after the curriculum reform, which began with the pilot offering of *Fundamentals of ECE* in the Spring of 2006 with a full offering of the new core curriculum in the Fall of 2006. Before the reform, the laboratory exercises were "cookie-cutter," recipe driven sets of tasks that students found minimally challenging. After a careful study of project-based learning and leveraging the expertise of the master teachers in an NSF program (TASC: Teachers and Scientists Collaborating (Math Science Partnership, PI Ybarra) focusing on the *inquiry process of learning* [4,5,6,7,9] the ECE faculty collectively agreed that our curriculum needed significant revision, particularly in the laboratory. As a result, the cookie-cutter, recipe driven laboratory exercises were replaced with pertinent, meaningful design projects that the students found fascinating. Students often spend more time (voluntarily) working in the lab than with their extracurricular activities. The department began instituting open lab hours enabling students to work with a more flexible schedule. Because the projects have no finality where they can say, "OK, I'm done. Time to go," students are driven to produce their best work and often spend many hours polishing their final projects.

In Table 4 core course grades are presented before (2004–2005) and after the curriculum reform (2008-2009). While there is nearly a uniform improvement in course grades, the most important

	Circuits/Fundamentals	Devices/Microelectronics	Digital Logic/Digital Systems	Electromagnetics	Signals & Systems
□ Pre-	88	93.5	92	0	95
■ Post-	92.9	96.0	95.6	94.8	93.8

Table 3. Core course laboratory grades before and after the departmental curriculum reform.

	Circuits/Fundamentals	Devices/Microelectronics	Digital Logic/Digital Systems	Electromagnetics	Signals & Systems
□ Pre-Reform	90.0	85.2	92.4	85.2	87.4
■ Post-Reform	92.0	94.4	91.4	93.1	89.9
n (post-)	89	38	70	47	63
n (pre-)	57	68	53	76	142
stnd. Dev. (pre-)	8.2	11.0	5.2	8.6	8.7
stnd. Dev. (post-)	9.0	5.3	4.5	5.6	7.0

Table 4. Core course grades before and after the curriculum revision.

aspect is that our core courses now demand significantly more creative output from the students [5] with open-ended class assignments and laboratory projects. This process engages the students more fully, and they are willing to spend more time and effort on their coursework, particularly in the lab.

UNDERGRADUATE RESEARCH

Hands-on research experiences are a hallmark of a Duke engineering education and enthusiastically supported by our faculty. More than 40% of our students participate in research through independent study and the premiere Pratt Research Fellows Program. The opportunity to participate in research is one of the most formative experiences an undergraduate can experience, and can impact students' academic performance, future educational and career decisions, and retention in engineering and the sciences. Prior to 1999, there was no formal undergraduate program offering research opportunities in all the majors at the Pratt School of Engineering nor was there a structured way for a student to do summer research. The Pratt Fellows Program was created to increase the amount of student undergraduate research at Pratt. From the beginning, the goal of the program was to make research easily accessible to students, to encourage student participation in all majors and research areas. Beginning in 1989, with the NSF funded Engineering Research Center for Emerging Cardiovascular Technologies (ERC) at Duke, we had had a student research program in cardiovascular biomedical engineering for undergraduates. As the NSF ERC funding phased out, Martha Absher wished to develop such a program school-wide in all majors at a much larger level of student and faculty participation. With the support first of Pratt Dean Earl Dowell, and his successor, Dean Kristina Johnson, in 1999 the Pratt Fellows Program commenced. Thus, a small student research program supported and created via a National Science Foundation Grant was broadened and leveraged into an innovative school wide program, and was incorporated into a formal part of the curriculum of the Pratt School of Engineering. Now, the Pratt Fellows Program is one of our integral features, one that makes Pratt distinctive among top 20 engineering schools due to the intensity and depth of the program, and serves as a recruitment tool for our very best applicants.

In addition to their extensive research, Pratt Fellows receive special opportunities and experience to develop their presentation skills, via poster presentations and a required formal research presentation that is filmed. New Pratt Fellows, in their first semester of research, are required to attend the Senior Pratt Fellows' Final Presentations, in which senior Fellows in their final undergraduate semester present a summation of their research projects to their faculty advisors, other faculty, research team members, and other interested members of the Pratt community. Thus, Senior Pratt Fellows serve as role models for the younger Fellows, providing important guidance and feedback.

Pratt Fellows focus their attention on state-of-the-art literature in their research area, and participate on their faculty's research team in every respect, including journal clubs, research and laboratory meetings. Pratt Fellows are strongly encouraged to prepare and submit publications as appropriate for their research project, and students contribute one, two and even three publications during their Fellowships. Students have even received patents for their inventions.

In ECE, in the mid- 2000's the issue was to take the existing Pratt Fellows Program and weave it into the research opportunities offered by the new curriculum focus on Integrated Sensing and Information Processing (ISIP). There had been a dip in interest in ECE research among ECE undergraduates, and as the new curriculum developed student awareness in ISIP areas, student interest in research resurged. Table 5 summarizes the number of ECE students participating in a formal independent study of research under the direction of an ECE faculty member as a function of semester. Students electing to continue independent research the following semester(s) are counted independently as Pratt Fellows are counted each semester of their participation.

The ECE curriculum redesign recognized the importance and value of Pratt Fellows. Students not in the Pratt Fellows Program heard about Fellows' research and outcomes, such as research papers, conferences attended, graduate school placements, and prestigious fellowships and scholarships won by Fellows, and this raised their interest in other research opportunities such as independent studies and classes in the new curriculum, even if these students did not chose to commit to the nearly two years of research required of a Pratt Fellow.

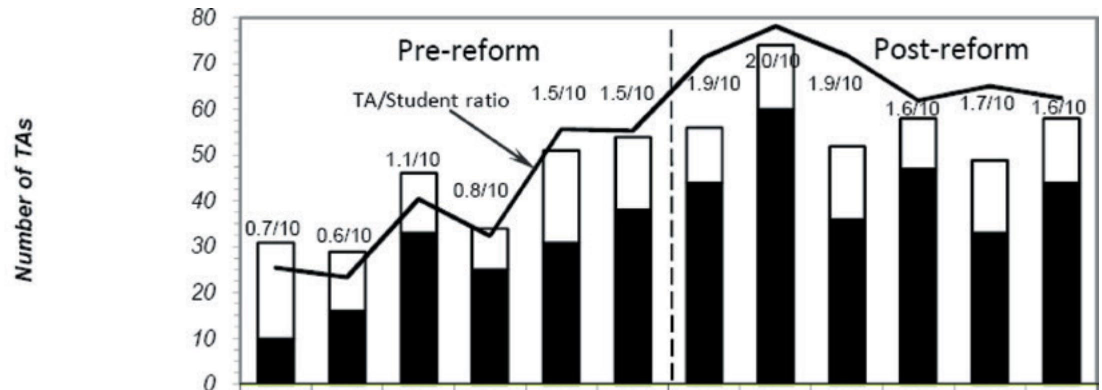
Examples of titles of student research projects include: The Use of a Discrete Transistor Amplifier to Produce Active Metamaterials, Active Microwave Imaging System for Breast Cancer Screening: RF MEMS Switching Matrix System Design, Enabling Realtime Location Privacy with Predictive Anonymization, and Designs and Simulations in Transformation Optics. Full student research papers are accessible http://www.ece.duke.edu/graduation-with-distinction

TEACHING ASSISTANT SUPPORT

As a result of the curriculum redesign, a significant increase in the number of teaching assistants is required. Table 4 shows the number of graduate and undergraduate teaching assistants that the department has utilized since 2003. It is clear that there has been an upward trend in the utilization of undergraduate teaching assistants (TAs). It has been our experience that undergraduate students, who have taken the course and done well, and who have strong communication skills with

Semester	*Seniors*	*Juniors*	*Sophomores*	*TOTAL*
Spr 09	20	17	0	37
Fall 08	21	3	2	26
Spr 08	10	13	1	24
Fall 07	7	4	0	11
Spr 07	12	7	0	19
Fall 06	13	5	0	18
Spr 06	10	7	0	17
Fall 05	8	1	0	9

Table 5. Formal ECE Undergraduate Student Participation in Research (not including paid research).



	F03	S04	F04	S05	F05	S06	F06	S07	F07	S08	F08	S09
GRAD	21	13	13	9	20	16	12	14	16	11	16	14
UG	10	16	33	25	31	38	44	60	36	47	33	44
TA/Student ratio	0.07	0.06	0.11	0.08	0.15	0.15	0.19	0.20	0.19	0.16	0.17	0.16

Semester

Table 6. ECE graduate and undergraduate Teaching Assistant positions utilized each semester along with a normalization of TA/student ratios since the fall of 2003. The graph in Table 4 also indicates when the curriculum reform began in the full core courses in the Fall of 2006. The large peak in the Spring of 2007 was primarily due to the significant TA resources needed to assist in the design and implementation of a set of Integrated Design Challenge (IDC) arenas for ECE 27.

the expressed motivation to be a TA for a given course, tend to perform exceptionally well. They take their TA responsibilities very seriously and are generally highly reliable. These TAs are critical to the success of our curriculum redesign because they are key facilitators of project work in the laboratory. And critical to the successful utilization of the TAs is the Undergraduate Laboratory Manager, who has overall responsibility for all of the undergraduate TAs. He meets regularly with the TAs in each course to ensure that the lab exercises and projects are progressing appropriately and provides guidance where needed. He also works directly with the course instructors to plan and execute the course's design project.

7. Conclusion and Future Work

This paper has presented details of the full-scale redesign of the undergraduate ECE curriculum at Duke University. The redesign was based on aligning the entire curriculum with the theme of Integrated Sensing and Information Processing because this theme simultaneously capitalizes on faculty expertise while addressing the three main areas of ECE. The ISIP theme provides a coherent, overarching framework that links principles of ECE to each other and to real-world engineering problems. In addition, the ISIP theme continues to unify the faculty by directly connecting their collective and individual expertise with their course content and providing motivation to understand and contribute to the content of courses feeding their own course and to those courses that follow. Descriptions of course evolution through the redesign process from the cornerstone first course *Fundamentals of ECE* through the core curriculum and finally the technical electives including culminating design courses have been provided. Assessment results have been provided indicating that significant improvement in self-reported student learning has resulted from the curriculum redesign (ability to design a component or system, ability to work effectively in teams). However, there remains work to be performed, and this will be a never-ending, ongoing process. The Modern Optics I course is an example of a technical elective that needs greater attention. The results presented indicate that very few students opt for the photonics Area of Concentration and that Modern Optics I does not produce students who perceive the course as developing their design ability, and it marginally develops team-building skills. There are other technical electives whose data was not analyzed. The ECE Department will pursue a complete analysis of every undergraduate course and continue its ongoing assessment and improvement process. Data was provided that indicated a significant increase in the number of teaching assistants required to support the new curriculum as well as a full-time Undergraduate Laboratory Manager. These resources are critical to the continuation of the new curriculum. The new ECE curriculum was recently accredited by ABET (fall of 2009).

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