2006-1373: A NOVEL INTRODUCTORY COURSE FOR TEACHING THE FUNDAMENTALS OF ELECTRICAL AND COMPUTER ENGINEERING

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A Novel Introductory Course for Teaching the Fundamentals of Electrical and Computer Engineering

Abstract

The Electrical and Computer Engineering (ECE) department at Duke University is undergoing extensive curriculum revisions incorporating both new content and organization and innovative teaching methods. The cornerstone of the new curriculum is a theme-based introductory course entitled Fundamentals of ECE. To introduce students to the major areas of ECE in their first year of study, this course has been organized around three concepts: 1) how to interface with the physical world, 2) how to transfer/transmit energy/information, and 3) how to extract/analyze/interpret information. Other goals include illustrating how various areas of ECE contribute to the design and functioning of an entire system, emphasizing the relevance of course material to real-world applications, and capturing the students’ imagination and creativity. To achieve these goals, the course adopts a unifying theme, tightly couples lecture and laboratory exercises, and includes a laboratory experience that emphasizes design, integration, and real applications. The course content and laboratory exercises were developed iteratively such that each component supported the other, rather than one being dominant and driving the other. A robotic platform was selected as the foundation of the laboratory experience. This platform enables the exploration of a broad range of ECE concepts, both independently and integrated into an entire system, is flexible, to encourage creative solutions, is capable of being applied to real-world challenges, and is easily connected to the curricular theme. This paper describes the curricular objectives and key course elements which guided the development of this course, the process by which the course was created, and the resulting content and structure.

1. Introduction

1.1 ECE Curriculum Redesign

The Department of Electrical and Computer Engineering at Duke University is undergoing a comprehensive curriculum redesign. Large-scale planning and development for the new curriculum has been conducted in earnest since early 2003. Before the redesign began, assessment of the existing curriculum identified six areas for improvement including: 1) a need to provide a coherent, overarching framework that integrates basic principles of ECE to serve as a roadmap through the curriculum, 2) a need to provide more guidance, through earlier, broader exposure to ECE, to assist students in the selection of technical areas of concentration, 3) a need for a more balanced coverage of fundamental areas of ECE, 4) a need for more flexible areas of concentration requirements, 5) a need to broaden design course opportunities, and 6) a need to better integrate the use of computational tools. To meet these needs, the overall structure of the curriculum has been redesigned around the theme of Integrated Sensing and Information Processing (ISIP). A theme-based curriculum facilitates the linkage of ECE topic areas to each other and to real-world challenges. Additional goals include incorporating innovative pedagogical techniques and hands-on experience throughout the curriculum while maintaining curricular flexibility.
While the redesign encompasses the entire four-year curriculum, a particular emphasis is on the students' early years in the core curriculum. Specifically, the foundation of the new curriculum is a first-year design-intensive course entitled *Fundamentals of ECE*. This course has been designed to provide students a holistic view of ECE by introducing concepts spanning how to interface with the physical world, how to transfer/transmit energy/information, and how to extract/analyze/interpret information. These concepts are developed within the context of the ISIP theme, introducing the framework that provides a roadmap for the remainder of the curriculum and providing a springboard that launches students into follow-on core courses.

1.2 Overview of other first year courses

The fundamental idea of introducing students to the broader field of Electrical and Computer Engineering in their first year is not unique to Duke’s new ECE curriculum. What varies among universities is the balance between rigor, or depth, with which the concepts are introduced and the breadth of topics covered. On one end of the spectrum are courses which focus on a single topic area, most often circuit analysis or signal processing. These courses provide a rigorous introduction to that specific area and often attempt to link this area to the broader field of ECE. However, for the most part, students are not introduced to other core areas of ECE with any rigor until subsequent courses. On the opposite end of the spectrum are courses that emphasize breadth, rather than depth\(^2\). While these courses introduce students to an array of topics which can preview later courses, they can typically be categorized as survey courses as students generally do not gain fundamental knowledge on which to build in subsequent, more rigorous courses. Some universities, including Duke University, have developed introductory courses which strive to give the students both breadth and depth, although the balance is still variable\(^5\).

2. Curricular Objectives of *Fundamentals of ECE*

The new foundation course, *Fundamentals of ECE*, is the first departmental course taken by students majoring in ECE. Upon taking the course, usually in their second semester, students have a minimal technical background including one semester of calculus and one semester of engineering computation (including MATLAB programming skills). Its critical role as the cornerstone of the ECE curriculum presents many challenges and opportunities to impact a student’s entire learning experience. The curricular objectives of this course, discussed below, were selected to ensure the development of a solid technical course whose content and delivery are tailored to student learning needs using innovative pedagogical methods and tools.

2.1 Rigorous Introduction to ECE

One of the most important criterion regarding the content of *Fundamentals of ECE* is that the course is a rigorous introduction to fundamental ECE concepts, not a survey course. Adhering to this principle proved to be quite challenging as the course was developed, given the course’s broad coverage of topics from the areas of circuits and devices, computer engineering, signals and systems, and electromagnetics. Through careful selection and organization of course topics, leveraging and integration of classroom and laboratory activities, and coordination between the development of this course and the other core curriculum courses, *Fundamentals of ECE*
successfully provides a solid technical foundation on which the remainder of the curriculum can build.

2.2 Curriculum Roadmap

The existing curriculum, like the curricula at many universities, begins with a first course focused on electric circuits. While many students find this course very interesting and intellectually challenging, the view of ECE as a field presented by this course is limited. This can negatively impact retention if, for example, a student does not find circuit design and analysis appealing and mistakenly assumes that this is what defines Electrical Engineering. Looking beyond the first course in the existing core curriculum, each area of ECE (e.g., signal processing or computer engineering) is presented in a separate course. Given the isolated nature of each core course, students do not necessarily develop an appreciation or understanding of how areas in ECE are interrelated. Furthermore, courses in some core areas, such as Electromagnetics, are often taken as late as the senior year after students have already committed to (and possibly completed) their areas of concentration.

By introducing all of the major areas of ECE in the first course and using the ISIP theme to illustrate how each area contributes to multiple components of an entire system, Fundamentals of ECE presents a broader view of the field and provides a roadmap for the curriculum. Furthermore, the course links each discussion of a concept, device, analysis technique, or system to later core and advanced classes that discuss that topic in more detail. This preview not only motivates future core and advanced courses, but it also enables students to identify their areas of interest earlier in their academic career and to select their future courses based in a principled experience-based manner.

2.3 Real-World Connection

Current engineering education literature suggests that exposure to real-world applications early in the curriculum is a key factor in student interest, long-term understanding and retention\textsuperscript{8-11}. However, standard curricula in which each area of ECE is presented in independent courses make it difficult to explore the relation of these areas to each other and to real-world challenges. Similarly, laboratory experiences can seem abstract and disconnected from the real world when the exercises are limited to one particular topic area. Because Fundamentals of ECE presents a broad spectrum of topics connected through the ISIP theme, integration of multiple areas of ECE in the context of real world applications is facilitated. In the laboratory, for example, students are not just taught how to build a circuit and measure a current or how to construct an amplifier or how to calculate the average value of a signal. Rather, students are taught the physical design and operation of a temperature sensor and how to build a circuit to condition the signal generated by the sensor and how to extract useful information from that signal to control another part of the system. The benefit of being able to use more realistic experiments in the laboratory also leads to more comprehensive discussions in the classroom and an overall more integrated experience. Through this approach, students are presented a holistic view of the field of ECE, which more accurately reflects real systems, and develop a greater understanding and appreciation of this interdependence.
2.4 Design Experience

The importance of design experience in an engineering curriculum has long been recognized. However, students often do not complete a hands-on, comprehensive design project until their senior year capstone design course. While this is obviously a very valuable and appropriate learning experience, students benefit from and desire earlier and more frequent real-world design experiences. One reason design experiences are often delayed is that students do not have the technical breadth early in their academic careers necessary to complete a comprehensive design project. While students in the first-year course, Fundamentals of ECE, do not have the breadth and depth to successfully carry out a completely open-ended design project with a level of sophistication expected from senior students, they do have enough knowledge to complete a project for which constraints and boundary conditions have been carefully emplaced to limit the scope while still requiring some degree of design. The laboratory component of Fundamentals of ECE, described thoroughly later in this paper, has been structured so that students are gradually introduced to sensor subsystems and fundamental design concepts in the first eight laboratory sessions followed by a five-week Integrated Design Challenge in which they must combine their choice of sensors into a single system to achieve a specified goal.

3. Key Course Elements

To achieve the stated curricular objectives, a variety of methods and tools have been used. One key element of Fundamentals of ECE is the use of a curricular theme to unify the course and provide a roadmap for the remainder of the Duke ECE curriculum, as well as to facilitate the connection between course concepts and real applications. Additionally, a tight coupling between the lecture and the laboratory components of the course is a key element achieved, in part, through careful course planning, the utilization of technology in the classroom, and the use of active learning techniques to more fully engage students in the learning process.

3.1 Curricular Theme: Integrated Sensing and Information Processing

A theme-based curriculum has been implemented at other universities with varying levels of success. The theme selected for the curriculum, Integrated Sensing and Information Processing (ISIP), provides a framework for studying individual ECE areas and facilitates the integration of concepts across areas. This theme bridges the disciplines of physics, devices, mathematics, electromagnetics, signal processing, computer engineering, communications and controls, with the goal of building systems and networks of systems for specific applications. Within the context of this theme, there is opportunity to explore ECE areas both independently and as integral components of the larger field. The ISIP theme also has the advantage of facilitating the exploration of sensing system design and operation without regard to traditional subsystem boundaries and interconnect structures – and thus it can be used in an educational setting to teach design and operation with much less regard to traditional course boundaries. Introducing students to the curricular theme in Fundamentals of ECE lays the groundwork for the remainder of the curriculum. Furthermore, this theme enables students to integrate what might otherwise seem to be a fragmented collection of concepts into a meaningful, holistic view of the field and provides an abundant source of real-world examples which can be used to
illustrate how these concepts contribute to the design and functioning of a complete, realistic system.

3.2 Lecture and Laboratory Integration

A fundamental and frequent problem in engineering education is the disconnect between theoretical lecture material and practical laboratory applications. Fundamentals of ECE was designed such that the distinction between lecture and laboratory content and activities is minimized. While the classroom continues to be the primary venue in which most new concepts are presented, some topics are introduced for the first time in the laboratory. Likewise, while hands-on experimentation remains the primary domain of the laboratory, modeling, simulation, and analysis of experimental data collected in the laboratory are incorporated into classroom activities.

To guarantee the integration of the lecture and laboratory components, Fundamentals of ECE was developed as a series of units consisting of two lectures and one laboratory exercise. This ensured a direct relationship between the topics discussed in lecture and those applied in the corresponding laboratory. In addition, students also complete “bridging” activities that link the two. Some of these activities are completed as homework assignments or as part of the laboratory report, while others are interactive classroom activities. Tablet PCs are used to facilitate the sharing of data and ideas between the classroom and laboratory environments, blurring the line between the two.

4. Course Organization and Content

Traditionally, each major area of ECE is covered in its own core course that is independent, for the most part, from every other core course. Students work their way through the curriculum, typically completing the set of core courses by their junior year. As mentioned previously, one obvious drawback to this curriculum organization is that students may not be introduced to some central areas of ECE, even at an introductory level, until late in their academic careers. Thus, one challenge in developing Fundamentals of ECE was to create a course that provided both breadth and depth to satisfy the need to aid students in constructing a “big picture” understanding of the field of ECE and the need to serve as the technical foundation for all subsequent core courses.

From the beginning, it was clear that the laboratory component of the course would be significantly different from the traditional, circuit-centric introduction to ECE. However, realizing the vision for the course also required a new, creative approach to content coverage and organization.

4.1 Content Coverage

Given the goal of presenting ECE concepts in an integrated manner, it was clear that the new course could not be taught by sequentially introducing circuits and devices, followed by signal processing, electromagnetics, and digital logic, or any other similar area-by-area organization. In other words, the syllabus could not be determined by simply lifting portions of the syllabi of existing core courses and appending them to each other. Rather, Fundamentals of ECE introduces concepts in a very integrated manner, an approach reflected in the structure of the
The laboratory experience and its integration with the rest of the course is critical to achieving the goals of the course and the curriculum, as is the relation between Fundamentals of ECE and the subsequent core courses. This interdependence necessitated a process by which the content and organization of the course evolved iteratively. The first step in the process involved the analysis of the current curriculum and its deconstruction into a list of concepts currently being taught. Next, these lists were prioritized, with legacy material eliminated and fresh concepts added. At this point, a group of faculty representing each major area of ECE reviewed the concept lists and selected a preliminary set of topics for the new introductory course. This set of topics, and the specific order of coverage, was modified as the laboratory exercises were developed. The resulting organization, which is unlike traditional courses, is critical to the success of the course as it emphasizes the interrelationships between major ECE areas and embodies the curricular theme. Through a synergistic presentation and organization of topics, students gain an understanding of each sensor/device at the physical level, then understand the input/output characterization or how the device operates at the system level, and finally gain an understanding of how the device interconnects with other elements as a component of a larger system.

4.2 Laboratory Experience

The ideal platform on which to base laboratory experiments enables the exploration of a broad range of ECE concepts, both independently and integrated into an entire system. The platform must also be flexible, to encourage creative solutions, capable of being applied to real-world challenges, and easily connected to the curricular theme of Integrated Sensing and Information Processing. After exploring several options, the use of a robotic platform rose to the top. Specifically, the laboratory experience of Fundamentals of ECE is based on the Parallax BASIC Stamp microcontroller. This particular platform was chosen, in part, because the number and variety of accessories (particularly sensors) is extensive. In addition, it is quite simple to program the microcontroller thereby allowing students to focus on the sensors and system design, rather than having to spend their time programming the robot. Other universities have also found robotics to be useful in introducing students to the field of ECE.14

The laboratory is divided into two major modules. The first module, containing eight week-long laboratory exercises, was designed to introduce students to the individual components of the robotic system. These components roughly correspond to the four central concepts on which the course is based: information gathering (focusing on how the robot uses sensors to interface with the physical world), information transmission (focusing on how the robot conveys information to a central location), information processing (how useful information is extracted from the data collected by the robot and used to make decisions or control the robot), and networking and information storage (how the robot’s data is managed and how multiple robots can be used to achieve a common goal). The second module, referred to as the Integrated Design Challenge, spans the final five weeks of the semester and requires students to design, build, and test a robot capable of performing a task (or series of tasks). To be successful, the robot must integrate concepts from each of the four major areas covered in the first laboratory module.
4.2.1 Introductory Modules

Through a series of eight laboratory exercises, students are introduced to a variety of sensors (e.g., temperature, pressure, IR pair), learn how to interface these sensors with the physical world in order to gather information, and learn how to store that information for later analysis or use that information to make decisions affecting the behavior of the robot. Each laboratory focuses primarily on one major concept area (e.g., physical devices or information transmission), but, due to the nature of the robotic platform, students naturally see connections between multiple major areas in each project.

In designing the eight laboratory exercises composing the “introductory” module, the goal was to engage the students in activities that reinforced concepts presented in lecture using real-world applications for motivation. In order to develop both the students’ conceptual understanding and their design skills, each laboratory session includes a more structured instructional component, in which basic concepts will be investigated, followed by a more open-ended exploration component, during which students will be challenged to design a robot that completes a real-world task. The relative portion of the laboratory session devoted to each component evolves over time throughout the semester from being primarily instructional, when everything in the laboratory is new to students, to being primarily exploratory, culminating in the Integrated Design Challenge.

**Laboratory #1: What is a Microcontroller?**

In the first laboratory session, students are introduced to basic laboratory techniques (e.g., breadboarding), learn how to program the BASIC Stamp microcontroller and establish communication between the computer and the robot. The robot is demonstrated to illustrate the range of sensors available and the types of activities it can be designed to complete. This provides a nice overview of the next seven weeks, providing motivation and inciting curiosity in the students. Finally, the students have the opportunity to gain some hands-on experience (and have some fun!) by programming the robot to perform a simple task, such as turn on an LED in response to the push of a button.

**Laboratory #2: A Scrolling Display**

The second laboratory focuses on digital logic concepts. The instructional component of the laboratory teaches the students how to wire and test a seven-segment LED circuit (using the BASIC Stamp platform) and use it to scroll the letters “ECE”. This is followed up by an exploratory component in which students are asked to implement a scrolling display capable of displaying a seven letter word.

**Laboratory #3: A Temperature Probe**

The third laboratory focuses on basic electrical measurements using a temperature sensor as the link to the real-world. The instructional component of the laboratory introduces students to basic test and measurement equipment (e.g., a DC power supply and a multimeter) and has them investigate and demonstrate Ohm’s and Kirchhoff’s Laws. The exploratory component challenges students to build, test, and verify the behavior of a temperature sensor circuit.
**Laboratory #4: Bumper Bots**
The fourth laboratory continues to introduce students to basic electrical measurements and introduces a second sensor, the pressure sensor. During the instructional component of the laboratory, students learn how to use a function generator and an oscilloscope and build and test a basic pressure sensor circuit. In the exploratory phase of the laboratory, students integrate the pressure sensor with the robot, ultimately designing a system that turns on an LED when the “bumper” of the robot collides with an object.

**Laboratory #5: Tone Generator**
The fifth laboratory illustrates concepts related to photonic devices and RC circuits. The instructional component of the laboratory has students explore the basic characterization of photoresistor and photodiode circuits and control these circuits with the microcontroller. The exploratory project asks students to design and build a system that converts average light level into a tone whose amplitude is proportional to the intensity of the light.

**Laboratory #6: Tachometer**
The sixth laboratory focuses on basic signal processing topics, such as frequency representation, sampling, and aliasing. The laboratory instruction guides students through an exploration of signal parameters (e.g., frequency, amplitude) using the function generator and an oscilloscope. The exploration challenge is to design and build a basic tachometer using a reflective switch and a fan.

**Laboratory #7: Remote Control**
The seventh laboratory focuses on basic communication concepts. Students are instructed on how to establish a two-way Bluetooth communication link between their PC and the robot that enables a string to be sent from the PC to the robot and back. In the exploratory component, students build a remote controller for the robot, based on Bluetooth communication.

**Laboratory #8: Light Tracker**
In the eighth and final laboratory of the introductory module, students explore control concepts. In the instructional component of the laboratory, students learn how to calibrate and control continuous-motion servo motors, building a robot that aims an infrared (IR) sensor pair at a moving light source. The exploration component of the laboratory challenges students to extend their system so that the robot chases the moving light source.

4.2.2 Integrated Design Challenge

The laboratory experience culminates in the five-week Integrated Design Challenge. For the Challenge, students (working in groups of two) are given a series of tasks that their robot must be able to complete. However, a single group does not complete these tasks independently. Rather, multiple groups are required to cooperate to complete the tasks. For example, a series of five tasks are assigned and each group must build a robot capable of completing each task. When it is time to test the robot, five groups (with five individual robots) are teamed together and must complete the tasks sequentially, with one robot activating the next upon completion of its assigned task. The group as a whole, as well as individual robots, is timed. Then, the task assignments rotate and the process is repeated until each robot has completed each task. In
addition to technical concepts, students will learn skills related to project and team management, whole-system integration, budgeting, and technical communication.

5. Assessment

The success of this course hinges on both its ability to achieve certain learning objectives and on its impact on student interest and engagement. Assessment of learning objectives is being done primarily through the use of exams. These exams include questions comparable to those asked of students who previously took courses covering the same topics in the existing curriculum so that comparisons can be made between cohorts. Exams have also been designed to reflect the tighter integration of the lecture and laboratory components of the course, such as by using a reference to a laboratory experiment to provide context for an exam question. A week or two after completing each laboratory exercise, students are asked to evaluate whether they believe that the activity has contributed to their understanding of the course material, enabled them to think critically about course material, and met stated educational objectives. Preliminary results for the first five laboratory exercises indicate that the majority of the students agree that these objectives are being met. Comments from the students include “The best aspect of this laboratory was how the theory that we learned in class related to our "real-world" experience of the circuit in the lab” and “This was my favorite lab so far because it really integrated everything very nicely.”

Student’s interest in, engagement in, and perception of the ECE field are being measured throughout the semester using surveys and instructor observations. After each weekly laboratory assignment, students indicate how well the laboratory was integrated with the lecture, how well it was related to the ISIP theme, and whether the exercise illustrated a real-world/practical application of the theory. Thus far, students have generally Agreed or Strongly Agreed that these goals have been accomplished. The assumption is that by achieving these goals, student interest and engagement increases. Further assessment and evaluation at the end of the semester is needed to determine if this assumption is valid.

In addition to the aforementioned assessment and evaluation, a comprehensive survey and a focus group discussion will be conducted by an external company at the end of the semester to solicit additional feedback from the students. Retention and enrollment data will be collected for this cohort of students as they progress through the curriculum and comparisons will be made with historic data. Not only will course selection be tracked, but the student’s confidence in their selection will be ascertained. It is anticipated that students who have been introduced to the breadth of ECE in an integrated approach early in their studies will make more informed decisions regarding which combination of ECE concentration areas is most relevant to their educational or career objectives.

6. Conclusions

A new approach to teaching first-year students the fundamentals of Electrical and Computer Engineering has been developed and piloted as part of the overall curriculum reform taking place at Duke University. The new foundational course, Fundamentals of Electrical and Computer Engineering, uses a theme-based, design-oriented approach to provide students with a rigorous, yet broad and integrative, introduction to the field. By carefully designing the lecture and
laboratory components of the course such that course concepts are explicitly connected to real-world problems, students begin to develop an understanding both of the relevance of theoretical concepts and the interrelatedness of various core ECE areas.

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2. All citations of courses in this section are intended to serve as examples, not exhaustive lists.

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