Teaching “Introduction to Electrical and Computer Engineering” in Context

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Invited Paper

In this paper we present an approach to teaching an introductory course in electrical and computer engineering to freshmen engineering students. The primary distinguishing characteristics of our approach include: providing information in an experiential context or “teaching-in-context”; focusing on “black-box”-based hierarchical decomposition as an approach to understanding complex systems; and using piece-wise linear models for nonlinear elements as a way to develop intuition and understanding about the workings of circuits. The experiential context is provided by having students carry out a series of laboratory exercises involving an exciting real-world electronic system. To date, we have developed laboratory exercises around a programmable robot and a Global Positioning System receiver. The greatest challenges in teaching an intellectually substantive course to entering freshmen are their lack, on average, of the mathematics and physics background that is taken for granted in most electrical and computer engineering courses. In this paper we demonstrate that by appropriate choice of material and presentation methods this challenge can be overcome.

Keywords*—Computer engineering, computer engineering education, education, electrical engineering, electrical engineering education, just in time, learning in context.*

I. Introduction

Over the past three decades, there have been significant changes in both the background knowledge and preparedness of students pursuing a Bachelor of Science (B.S.) degree in electrical and computer engineering (ECE) and in the core body of material that defines this field. In fact, three decades ago, most universities would have had Departments of Electrical Engineering, and a few would have had Departments of Electrical Engineering and Computer Science. However, few if any universities would have had Departments of ECE. Given these changes in both the nature of the entering freshmen and the nature of the field of ECE, it is important to reevaluate the way in which we deliver the four years of education that typically leads to a B.S. degree in ECE. One of the tenants of most B.S. curricula is that entering freshmen interested in pursuing a B.S. degree in ECE should spend their freshmen year taking preparatory mathematics and science courses, which are then prerequisites for courses in ECE. This effectively prevents most entering students from taking any engineering courses during their freshmen year. The implicit assumption in this arrangement is that until students have had sufficient background in mathematics and science, they cannot begin their studies of engineering. In this paper we argue that teaching an intellectually substantive first course in ECE to freshmen is possible. We will also argue that teaching an intellectually substantive introductory ECE course to freshmen offers a number of benefits to both the students and to the faculty.

We will support the above assertions by describing the intellectually substantive course we developed, “Introduction to Electrical and Computer Engineering,” which is taken by freshmen engineering students at Carnegie Mellon University (CMU). This course was developed with the view that students knowing only basic algebra and high school physics should be able to succeed in the course. One way to approach this goal would be to present a superficial coverage of a broad range of ECE material while motivating and familiarizing students with electronic components via a series of laboratory exercises, i.e., a survey course. Although this is a laudable approach, we also wished to engage freshmen in the intellectual underpinnings of ECE, e.g., Kirchhoff’s laws, linear superposition, nodal analysis, device I–V modeling, Karnaugh maps, etc. After careful consideration, we concluded that there are a number of important ECE topics that can be taught in an intellectually substantive way to freshmen knowing only basic algebra and high school physics. Also, there are some ECE topics that simply cannot be included, e.g., teaching students to analyze the time-domain behavior of R-L-C circuits in an intellectually substantive way requires that the students have an understanding

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of differential equations. The last challenge that we faced was selecting a subset of ECE topics that could be taught to freshmen and fitting them together in order to create an interesting and coherent overview of both electrical engineering and computer engineering.

The remainder of this paper is structured as follows. Section II discusses some of the factors that motivate teaching an introductory course in ECE to freshmen. Section III presents the basic organizing principles underlying our vision of how to give freshmen an introduction to ECE; and it presents the specific details of the "Introduction to ECE" course offered at CMU. In Section IV we present some observations about the course and offer concluding remarks.

II. Motivations for "Introduction to ECE"

As we observed in Section I, over the past three decades there have been significant changes in the nature of students pursuing a B.S. degree in ECE and in the core body of material that defines ECE. These changes have resulted in a number of stresses on educational institutions offering a four year B.S. degree in ECE. In this section, we discuss some of these changes and indicate how they provide a strong motivation to educational institutions to offer an introductory course in ECE to freshmen. Although our observations are drawn from our experiences with freshmen entering the Carnegie Institute of Technology, CMU's Engineering College, discussions with our colleagues at other institutions of higher learning suggest that these observations are true at schools ranging from elite private research universities to large state universities to four-year teaching colleges.

A. Math and Physics Background of Incoming Engineering Freshmen

In the context of creating an introductory course in ECE, one of the most salient features of the incoming freshmen is their background in mathematics and science. In general, there is an extremely high diversity in the mathematical background of entering students. Some have already had the equivalent of two semesters of calculus and one semester of differential equations. Others have had nothing more than high school algebra, geometry, and trigonometry. Even though nearly all entering students have had high school algebra, we still find that solving two equations in two unknowns requires review and practice before a majority of students become comfortable solving this type of problem. Nearly all of the entering freshmen understand sinusoidal functions such as $\cos(\omega t)$. Nearly all entering students have had some background in elementary Boolean algebra; e.g., they are familiar with truth tables and know about many of the Laws of Boolean algebra. We find that almost all students have had some kind of high school physics. In general, entering freshmen have some understanding of voltage, current, electrons, and charge. However, a significant number of entering students do not have any experience or understanding of basic electronic components such as resistors, capacitors, or inductors.

B. Experiential Background of Incoming Engineering Freshmen

Another extremely important aspect of the nature of incoming engineering freshmen is their real-world experience with electronics and computers. During the past 30 years, there has been almost a complete reversal in the experience levels of incoming freshmen engineering students between electronics and computing. Thirty years ago, relatively few students graduating from high school had significant experience programming computers or had significant exposure to computer hardware. This lack of experience was primarily driven by the high cost of computing systems in those days (high schools could hardly afford their own computer) and by the high complexity of programming these computers. On the other hand, a majority of the entering freshmen had build some kind of electronics kit; e.g., a Heathkit radio or television receiver. Most high school students interested in pursuing a B.S. in ECE would have had some direct hands-on experience with basic circuit components. This ability to create an interesting electronics system from a kit greatly helped entice students into the field. In fact, it is well documented that students retain and integrate course material related to their own personal experiences much more successfully than unrelated material [3]. Thus, our freshmen introductory ECE course must be designed to provide an experiential context for the development of theoretical material [1], [12].

Today, a large fraction of the incoming freshmen pursuing a B.S. degree in ECE have never soldered components onto a printed circuit board. In fact, many of them do not even know what a resistor looks like or what the resistor color code is. Unfortunately, the complexity of modern electronics has resulted in millions of basic circuit elements being encapsulated in a single plastic integrated circuit (IC) package whose insides are completely inaccessible to the student. The determined student who tries to build something interesting from discrete resistors, capacitors, and transistors quickly discovers that constructing an interesting electronic system requires an overwhelming number of components.

The situation in the field of computer engineering has also reversed. Virtually every single incoming freshmen pursuing a B.S. degree in ECE knows how to program a computer in several different programming languages and is quite familiar with the hardware components of computing systems. Note, another way in which students gain experience is through part-time and summer jobs taken during their high school years. However, in today's economy, a high school student is far more likely to be hired to work with either computer or network hardware or software than to work in a firm carrying out electronics design. This too means that entering students are far more likely to have experience in the computer engineering (CE) area and less likely to have had experience in the electrical engineering (EE) area.

C. Lack of Knowledge About the Practice of Engineering

While freshmen entering the College of Engineering at CMU are usually highly motivated, many of them do not have a clear understanding of what undergraduate studies in engineering are all about. Some have been encouraged to pursue an engineering career with little understanding of what that entails. Many are interested in engineering, but do not have a clear idea of which engineering discipline is for them. This lack of understanding on the part of freshmen was not being alleviated by course work because, as at most universities, freshmen engineering students were typically taking only preparatory courses such as physics and mathematics. This meant that many students had to wait until their sophomore year to take their first course in engineering. A negative aspect of having sophomore entry-level classes is that students who really do not end up liking the particular engineering department in which they elected to major can be trapped in that major; or they may require more than four years to complete their B.S. degree if they choose to switch majors.

As long as the "Introduction to ECE" course for freshmen provides students with an overview of what ECE is all about, students can make decisions about switching majors an entire year earlier. Carrying this one step further, all of the departments in the College of Engineering at CMU have created introductory courses for their departments to be taken by freshmen. Incoming engineering students are required to take introductory courses from at least two different engineering departments during their freshmen year. This gives students a much broader understanding upon which to make their choice of a specific engineering department in which to major. For those who discover that engineering is not for them, this approach helps them to discover that fact by the end of their freshmen year.

Another intellectual barrier the is often posed by incoming students interested in pursuing a B.S. degree in ECE is their common presumption that EE and CE are two separate disciplines which have just been collected into one department for convenience. We frequently have entering students who are planning to pursue a career in CE asking why we are trying to teach them anything about electronic circuits. And, to a lesser extent, we have entering students who are planning to pursue a career in EE asking why we are trying to teach them anything about 1's and 0's. In order to combat this compartmentalized view of EE and CE, an "Introduction to ECE" course should attempt to maintain a balance between EE and CE content; moreover, it should highlight the interdependence between EE and CE. Students need to understand as early as possible that they are pursuing a B.S. degree in electrical *and* computer engineering. Fortunately, this view is supported by the fact that many educational institutions, CMU included, offer a B.S. degree in ECE rather than offering separate B.S. degrees in EE and CE.

D. Lack of Patience

Whether unfortunate or not, it is a fact that we live in an age of instant gratification. Students are not significantly motivated by the admonition that studying mathematics and science for the first year will prepare them to embark upon engineering course work in their sophomore year. Students subjected to this type of program frequently complain that "I came here to study engineering, and all you taught me was math, chemistry, and physics!" More than complain, many freshmen will give up on engineering as a career before they have ever even taken a single engineering class. By offering an "Introduction to ECE" course for freshmen, we have the chance to demonstrate to them just how exciting engineering can be. However, in order to entice students to pursue careers in ECE, we must make any introductory course exciting for the students. It must present material in an accessible way and it should employ interesting design vehicles that can capture the student's imagination.

E. Lack of Good Study Skills

The study habits of first semester freshmen vary from nonexistent to extremely sophisticated. Unfortunately, it has been our experience that a significant number of entering engineering freshmen at CMU are smart enough that they never really had to develop good study skills in order succeed in high school. Therefore, when they come to CMU and take "Introduction to ECE," we must adjust to the fact that they are busy learning good study skills at the same time they are learning ECE. Freshmen introductory courses need to take this into account and need to help students learn necessary study skills.

F. Increasing Volume of Core ECE Material

Over the past 30 years, the amount of core material that is essential for electrical and computer engineers to master has grown at a remarkable pace. In addition, how specific topics are taught has also changed rapidly; e.g., the active devices we teach students about now are MOS transistors instead of vacuum tubes. Many have argued that there is so much core material that it cannot all be covered in a four-year B.S. degree program [11]. Many industrial employers also agree. For example, a majority of the companies hiring students for circuit design positions will only interview students who will be receiving a Master's degree or a Doctorate in ECE. Several of these companies have indicated that the additional course work and project work associated with the Master's degree is necessary in order to decrease the time required to train the newly hired students.

Given that there is significant pressure to include even more material in a four-year B.S. degree program, it seems only natural to try to start teaching core concepts of ECE during the freshman year. However, if this strategy is to provide any real help, then core ECE material must be covered in an intellectually substantive way. A purely survey-type introductory course would not add significantly to the total amount of material that could be covered in four years. The other important aspect of ECE is that there has been, and continues to be, rapid evolution in the underlying ice hardware in many areas. This highlights the importance of teaching B.S. students the fundamental underlying ideas so that they are prepared to adapt as the underlying technology changes. For example, in the circuit design area students need to learn how to analyze and design assemblies of electronic components—whatever their individual device characteristics. This type of thinking can be greatly facilitated by teaching students to view electronic circuits in a black-box-based hierarchical way. Hierarchical decomposition encourages the student to separate the ideas related to how components interact through wires from ideas about how the devices operate. For this reason, a student well versed in hierarchical design of circuits using MOS transistors should be able to learn about a new quantum electronics device and to apply his or her MOS transistor knowledge to the design of circuits using these new devices.

III. CMU's "Introduction to ECE"

In the late 1980's, because of the above shifts in the both the field of ECE and the experiences of incoming freshmen engineering students, we found it increasingly difficult to teach the sophomore entry-level course in ECE at CMU, "Electronic Circuits I." In this course, we were attempting to teach students about basic circuits, followed by diode and transistor circuits. We presented diode and transistor operation in the context of hole and electron drift and diffusion currents in semiconductor devices. Many students just did not seem to "get" the importance of the fundamental relationships we were describing to them. They could see no possible practical use for the material we were requiring them to learn. Part of the problem was the students' lack of an experiential context for the material we were covering. Part of the problem was the particular topics we chose for this class; e.g., a detailed discussion of drift and diffusion currents was hard to grasp for students who really had little experience with current in general.

In 1991, the CMU ECE Department decided that this problem should be addressed by having freshmen take an "Introduction to ECE" class that was designed to make sure that all freshmen pursuing a B.S. degree in ECE had, at a minimum, a set of experiences involving the basic elements of both EE and CE. All of the subsequent courses could be designed much more efficiently because they could rely on the students having been exposed to a certain body of knowledge and to a certain set of real-world experiences with electronic components. Contrast this with the case where all of the sophomore courses in a department must individually cope with a highly diverse set of student backgrounds. In fact, the course "Introduction to ECE" is part of a new four-year curriculum that CMU's Department of ECE instituted beginning with the 1991–1992 academic year [11]. The courses that students take after "Introduction to ECE" have all been revised to take advantage of the vastly improved level of preparedness of the students who have completed the introductory course. Our new "Introduction to ECE" course not only provided following courses with a more uniform student background, it also provided students with a significant understanding of several important topics in ECE.

In this section we present the specifics of the "Introduction to ECE" course that we developed. First we will present a list of goals that we wanted to achieve with our introductory class. Next, we will outline some of the philosophical ideas that guided us in creating the introductory course. We will then present specific details describing the topics we chose to address in the course. This section ends with descriptions of the two different laboratory projects that have been developed for this course, a mobile programmable robot and a Global Positioning System (GPS) receiver.

A. *Goals for the "Introduction to ECE" Course for Freshmen*

Collecting all of the goals and constraints for an "Introduction to ECE" course for freshmen from Section II, we have the following.

- The course must be accessible to freshmen knowing only simple algebra and high school physics.
- The course must give freshmen hands-on experiences with as many of the elementary components of ECE as possible. These experiences should be carefully designed to provide the best possible context for the development of theoretical material. Further, the course should only introduce theoretical material when the appropriate context has been established.
- The course should give freshmen a realistic idea of what ECE is all about. In particular, students should have opportunities to carry out engineering design, albeit in a constrained context, in addition to learning analysis techniques throughout the course.
- The course should attempt to maintain a balance between EE and CE content and further, should highlight the interdependence between EE and CE.
- The course should expose freshmen to ECE in an exciting and stimulating way. Students should have "fun" learning about ECE. Students should be motivated to learn the material.
- The course should realize that entering freshmen may have poor study skills. Features should be incorporated into the course to minimize the impact of their poor student habits and to help the students learn good study habits.
- The course must teach students intellectually substantive core ECE material. Simply providing a superficial survey of topics in ECE is not sufficient.

Satisfying all of these objectives simultaneously proved to be quite challenging. However, as we shall see later in this section, it was not impossible.

B. *Philosophical Guidelines*

There are a number of important philosophical guidelines that we followed in trying to put together a freshman introductory course that satisfied all of the goals enumerated above. The first and foremost idea is that students learn best when the fundamental theoretical ideas of ECE are taught in the context of their real-world usefulness. Much of the research on human learning clearly suggests that theoretical ideas are much easier to learn when the student already has experience with the variables and elements which are the object of the theory [3]. In addition, when fundamental theoretical understanding is closely coupled to real-world experiences, the student is also more able to reason about how this knowledge could be used to solve different problems [3]. Thus, when one reveals Ohm's Law—a simple linear relationship between voltage, current, and resistance—to students with no experience with resistors, they dutifully record it in their lecture notes and may even try to memorize it. Yet they do not really internalize this knowledge in such a way that it makes connections with their main body of working knowledge. Contrast this with the case of a student who has had some experience with resistors. For example, he or she has placed a 1-, 10-, and 100-Ω resistor across a 1.5-V battery and discovered that the 100-Ω resistor remains cool, the 10-Ω resistor becomes slightly warm to the touch, and the 1-Ω resistor can burn your finger tips. When this latter student is taught the equation for the power dissipated in a resistor ($P = V^2/R$), he or she not only memorizes the equation but really understands the meaning of the equation and its practical application. In order to provide both real-world experiences and fundamental theory, we strongly believe that an introductory course in ECE for freshmen should be constructed around lectures and recitations to present the fundamental theory and a closely integrated set of regular laboratory sessions to provide the real-world experiences.

The second philosophical guideline that we followed is that for maximum teaching effectiveness, fundamental theory must be delivered using a just-in-time teaching strategy [2]. Under a just-in-time teaching strategy, fundamental theoretical ideas are introduced just when the student's experiences are creating a need for that theory. This requires extremely careful coordination between the specific experiences students have in the laboratory and the fundamental theoretical material that they are taught in lectures. The exact sequence of laboratories and lectures must be ordered to provide effective just-in-time teaching. Our goal is to provide the students with the opportunity to gain some experience with real world behavior of electronic elements while they are also being taught the theory that provides order and understanding to their observations in the laboratory.

The third philosophical guideline is that the course should emphasize a top-down black-box teaching approach so as to provide students with a high-level, systems-oriented view of the material. In order to engage the student's interest, the laboratory exercises should be focused on a complex system to which students can relate. For example, one set of laboratory exercises that we have developed focuses on the design of a mobile programmable robot. The specific complex system selected as a focus for the laboratory exercises should be used to illustrate how complex systems can be decomposed into subsystems. In the lectures we develop the theory behind the operation of each of these subsystems. In the laboratory we explore, construct, and test these subsystems, thereby gaining experience with their operation. By the end of the set of laboratory exercises the students have completed the construction of the entire complex system. A description of the high-level system behavior provides a context (and also arouses a student's curiosity) within which to understand how various elements are combined in a circuit to achieve the desired behavior. The course should focus on black-box models of complex systems, black-box models of their constituent subsystems (e.g., power supplies, sensor circuits, etc.), and finally black-box models of primitive circuit elements (e.g., resistors, diodes, transistors, etc.). In the context of learning about the input–output behavior of the circuit elements, we should introduce Ohm's Law, Kirchhoff's voltage, and current laws, and implicit techniques for circuit analysis.

The fourth philosophical guideline is that the course should employ only linear and piece-wise linear (PWL) circuit analysis methods. Although students can solve networks of linear circuit elements by hand using only simple algebra, as soon as we consider nonlinear circuit elements such as diodes or transistors, linear circuit analysis fails. However, in keeping with the black-box behavioral modeling viewpoint, we advocate modeling all nonlinear elements with PWL models. PWL models for diodes and bipolar transistors are straightforward to teach, and relatively few PWL segments can create relatively accurate models of behavior. For example, the diode model only requires two regions of operation: ON (the diode is a battery) and OFF (the diode is an open circuit). Bipolar transistors are somewhat more complex because they are three terminal devices. However, most of the common modes of operation of a bipolar transistor can be covered by three PWL model regions: OFF; forward active; and saturated. PWL models for MOS transistors deep in velocity saturation are also straightforward to develop, and PWL models of long-channel MOS transistors can be developed that are valid within any desired region of operation. Remember, within any one region of operation, analysis of circuits containing PWL models reverts to solving a linear circuit (a skill students have hopefully already mastered). It must be noted that the behavioral models of a transistor and a diode are introduced without ever introducing the concept of holes, electrons, doping, etc. This is because: 1) these notions are not required to understand the behavior of a diode or a transistor and 2) the context for introducing these ideas has not yet been established. Rather than complex equations whose analysis would be beyond the hand calculations of freshmen, we employ PWL models for all devices.

A fifth philosophical guideline that we followed was that there should be a balance between EE material and CE material covered in the course. One of the important points we wanted to stress in any introductory ECE course was the connection between analog and digital systems. Traditionally, students are exposed to analog systems in the guise of circuit analysis in an introductory circuits course and then exposed to digital systems in a different introductory course. Our approach is very different. We feel that students must appreciate the connection between analog and digital systems, and we believe that including both EE-related material and CE-related material in the same introductory course helps to achieve that goal.

The last philosophical guideline that we consider is to only include course material that will be accessible to nearly all of the incoming freshmen engineering students. In essence, the point of this guideline is to try to select intellectually substantive core ECE topics to be covered that will not rely on prerequisites that some of the entering freshmen will not have had. For example, we cannot talk about the transient behavior of analog circuits without introducing the notion of differential equations. However, we can analyze the input–output transfer function for many complex circuits using nothing more than PWL models and simple hand analysis of linear systems. Note, as will be seen below, that two of the laboratory exercises associated with the laboratory exercises require that the students understand the transient charging of an *RC* circuit to a fixed potential. We do introduce the concept of a first-order exponential response in class; however, we do not hold students responsible for that material on their tests or problem sets. Similarly, for the GPS receiver lab, we also need to introduce the concepts of frequency and radio wave propagation. Again, we do this at a behavioral level as the students are not adequately prepared for a technically deep presentation of this material. Interestingly, very few students have any trouble with simple discrete-time equations. Therefore, when discussing digital circuit design we can include coverage of both flip flops and general finite state machines.

C. Overall Course Organization

In this section we describe the course "Introduction to ECE" as it is taught to entering freshmen at CMU. This example is presented to demonstrate that it is possible to pick an intellectually rich set of core ECE concepts to teach freshmen without requiring college-level prerequisites in mathematics and physics. However, our particular selection is by no means unique. It may be possible to pick other sets of topics that would also satisfy our philosophical goals. Our course "Introduction to ECE" is a 12-unit (or four-credit) course and consists of two 80-min lectures, one three-hour laboratory session, and one 50-min recitation session per week for 13 weeks. All ECE majors are required to take this course and it is a prerequisite for the more traditional circuits and digital systems courses that follow. Although there are a number of other topics that we would like to include in this course (e.g., the internal operation of CMOS digital logic circuits), we have found the set of topics below completely fills the semester. Also, we have learned over the years that covering fewer topics in more detail is vastly better when teaching freshmen. If one attempts to rush through the material below in order to add in new topics, the students may not learn any of the material as well as they can when it is presented at a slower pace.

The following is a list of the topics within ECE that we have selected to include in "Introduction to ECE" and a brief set of ideas associated with of each the topics. They are listed in the order that we present them in the lecture and laboratory exercises.

- Introduction: electronic system and circuit design; hierarchical decomposition of designs.
- Basic Circuit Elements: current and voltage; circuit schematics and symbols; resistors and Ohm's Law; independent voltage sources; independent current sources; power equation and reference direction.
- Circuit Analysis: nodes, branches, and loops, Kirchhoff's current law (KCL); Kirchhoff's voltage law (KVL); the node method; floating voltage sources in the node method.
- Resistive Networks: resistors in series; the voltage divider; resistors in parallel; the current divider; series/parallel reduction of resistor networks.
- Two-Terminal Networks—Equivalent Circuits: linear superposition; thevenin equivalent circuits; Norton equivalent circuits.
- Dependent Sources: dependent voltage sources; dependent current sources; analysis of circuits containing dependent sources.
- Diodes and PWL Models: diodes; graphical solution of diode circuits; PWL models; PWL models of diodes; solving diode circuits using PWL diode models.
- Modeling Bipolar Transistors: behavior of the transistor (I–V curves); PWL model for the transistor; load-line analysis of a bipolar junction transistor (BJT) circuit; PWL analysis of transistor circuits.
- Transistor Circuits: transistor circuit overview; common base; common emitter (CE) amplifier; common collector (CC); CC + CE transistor pair.
- Amplifiers and Operational Amplifiers: amplifier black box models; operational amplifiers (op amps).
- Binary Logic Circuits: voltage levels and logic levels; common emitter amplifier as logic gate; diode–transistor logic (DTL) gate.
- Combinational Logic: overview of logic gates; special arithmetic gates; overview of Boolean algebra; DeMorgan's theorems; standard forms; useful combinations of basic gates; using Karnaugh maps; arithmetic circuits and Karnaugh maps.
- Sequential Logic Circuits: why computers need memory; flip-flop design; data registers; static RAM (SRAM); counters; shift registers.
- Finite State Machines (FSM's): FSM's using next state and output mapping logic; FSM's with external inputs.

By the time students complete this introductory course, they will be able to analyze basic circuits that include resistors, ideal operational amplifiers, transistors, and diodes. They will have a basic understanding of the workings of operational amplifiers, logic gates, flip-flops, SRAM's, counters, and logic control circuits.

It is obvious that the first few lectures introducing basic analog circuit ideas and the first few lectures introducing basic digital logic circuit ideas are similar to lectures in traditional introductory courses in circuit analysis and digital systems, respectively. One might then ask, what is different? The first difference lies in the presentation and the manner in which details are introduced. Students are introduced first to an application (i.e., a power supply), then how it works, followed by details of the elements that constitute the circuit. Consequently, they are introduced to transistors and diodes without studying the physics of solid-state devices. New ideas are introduced only when they are needed—just in time—and more importantly, they are well motivated in the context of an application or need. For example, the concept of PWL models is not introduced until students have discovered that graphically solving circuits containing diodes is extremely time consuming. This directly motivates development of PWL models and their use to make solving circuits containing diodes much easier.

Although we can motivate the introduction of improved analysis techniques in lecture by having students first analyze circuits the "hard" way, in order to fully achieve our goal of having the students' experiences motivate the lecture presentations of fundamental theoretical ideas we must have a set of laboratory exercises tightly linked to the lecture presentations. These laboratory exercises provide both hands-on experience and help students to develop insight into the working of a system or a circuit. The sequencing of the laboratory exercises must be perfectly timed with the theoretical developments in the lectures. The lecturer cannot fall a week behind in lectures when running this course without diminishing the quality of the overall experience for the students. For example, while a power supply is being introduced and discussed in the lectures, the students are building, testing, and debugging a power supply in the laboratory. The laboratory exercises are also designed to show the student how systems are built and tested in a methodical manner. In the next two sections we will describe the two different sets of laboratory exercises that we have integrated with the above set of lectures to form the "Introduction to ECE" class.

D. The Programmable Robot Lab

We first chose a simple robot system (Graymark Robot Kit Model 603A [13]) for the laboratory exercises to motivate and facilitate the teaching of basic concepts such as KVL, KCL, dc models of circuit elements, logic gates, flip flops, counters, digital logic, etc. The small mobile programmable robot we chose as the focus for this set of laboratory exercises is capable of making right and left turns, moving in a straight line, flashing a small light, and beeping. A photograph of the complete robot kit is shown in Fig. 1. A portion of the subsystems that comprise the robot, shown in Fig. 2, provide the basis for interesting laboratory exercises. Since they include both analog and digital circuits, they allow us to provide an integrated view of ECE. The robot system is simple enough for the freshman to understand and at the same time complex enough for us to convey to the student the big picture of what ECE is all about. Finally, the robot system is entertaining enough to keep the students motivated. Toward the end of the semester, when a completely working system has been realized, students are asked to add some hardware to the robot or to program it in creative ways to make it do interesting things. This will be the final project for the course and students will have a large degree of latitude in defining it. The sequence of laboratory exercises are as follows.

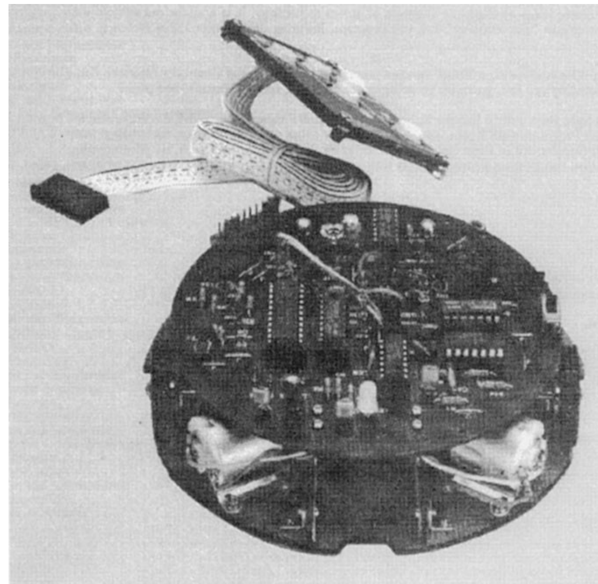

Fig. 1. Photograph of the programmable mobile robot used in the laboratory exercises.

- Introduction and Getting Organized: This lab session familiarizes the students with the lab, their lab teaching assistant, and the test equipment and tools they will be using during the course. During this lab session the concepts of hierarchical decomposition, black-box modeling, voltage, and current are being introduced in lectures.
- General Circuit Construction Guidelines and Practice: This lab session actually teaches students how to solder. Students practice extensively on scrap printed circuit boards. During this time the lectures are introducing the resistor and the relationship it imposes on voltage and current.
- Current and Voltage: This lab session familiarizes students with power supplies, batteries, resistors, and the digital multimeter (DMM). Students measure the voltages in a number of circuits. Students explore the behavior of different value resistors and they use the DMM to measure both current and voltages in their circuits. This lab work is closely linked with the presentation of Ohm's Law in lectures.
- Diodes: This lab session explores the I–V relationship of small signal diodes and Zener diodes. Students analyze several simple circuits containing diodes. This lab work motivates the development of PWL models for diodes in lecture.
- LED Driver—Transistors as Switches: This lab session introduces the bipolar transistor as a switch to control a light emitting diode (LED). Students measure the I–V curves for the transistor to gain a feeling for its operation. This lab work motivates the development of a PWL model for the transistor in lecture.
- Voltage Regulator—Transistors in Forward Active: This lab session uses a Zener diode and a BJT in order to construct a simple voltage regulator for the computer control circuitry of the robot. Students explore the operation of the BJT in its forward active mode.

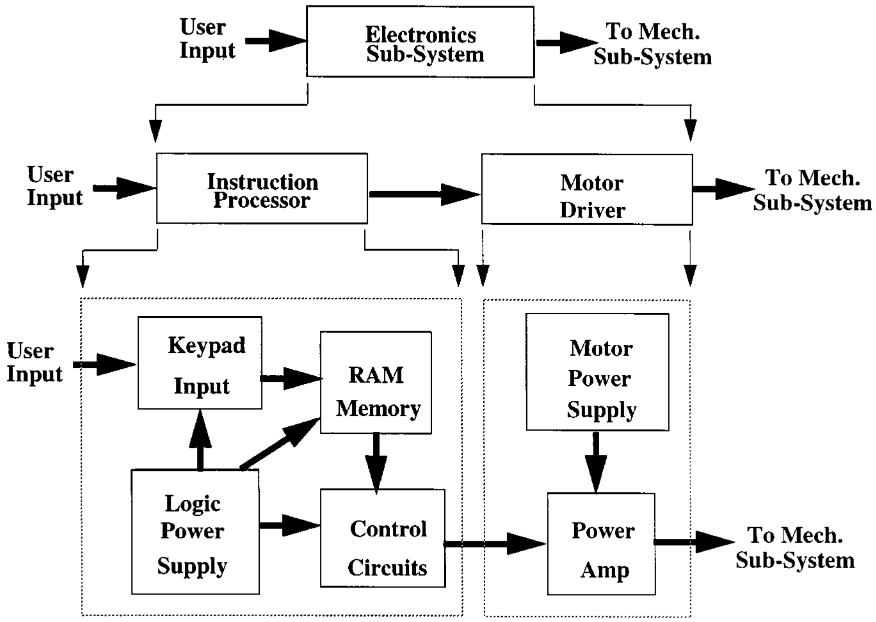

Fig. 2. Block diagram for a portion of the programmable mobile robot.

This lab work motivates the need for a general method for solving circuits containing multiple PWL elements presented in lecture.

- Motor Driver—Multiple Transistor Circuits: This lab session uses two BJT's in series (common collector followed by common emitter) to drive the robot's motor. This lab exposes students to the conversion of electrical energy into mechanical force. The lab work motivates continued practice with solving circuits containing multiple PWL elements.
- Operational Amplifiers—Higher-Level Analog Functional Blocks: Op amps are introduced here as an example of how many transistors can be integrated together to create a higher level functional block. Students learn that the observable behavior of the op amp does not really depend on the exact circuit schematic of the transistors inside. This lab work motivates the black-box view of circuits and systems promoted in lecture. It also creates a bridge to the digital world as students operate the op amp without feedback in the lab—in which case it is like a comparator converting signals from the analog world to the digital world. These observations in lab motivate the definition of analog representations of digital signals that is presented in lecture.
- Clock Generation—Inverters, Capacitors, and Resistors: This lab introduces students to CMOS inverters which closely approximate an ideal logic gate. Students also place simple *RC* high-pass and low-pass circuits between a pair of digital inverters in order to create a rising-edge triggered pulse generator and an edge delay circuit respectively. Finally, students place an *R* and a *C* in a feedback loop around three inverters in order to generate a free-running oscillator. This lab work motivates the operation of inverters as logic gates in lectures. However, it also violates the list of topics we selected for lectures. In lecture we formulate the differential equation and to solve it for step inputs. Students without any background in differential equations simply have to accept the solution as presented. In keeping with the philosophy of the course, the students are not responsible for this material on tests and problem sets. Of course, they do need to at least memorize how these circuits work in order to complete the lab exercise.
- Speaker Driver—Tone Generator: This lab covers the design of a gated tone generator that causes a small piezoelectric speaker on the robot to "beep." It uses a very similar circuit to the clock generator for an oscillator but adds the use of a PNP transistor in order to gate the free-running oscillator on and off. During this lab, the lectures are moving ahead with truth tables, logic gates, and Karnaugh maps.
- Logic Gates: In this lab students construct and measure the truth tables for a number of different logic circuits constructed from CMOS digital logic integrated circuits. This experience reinforces the lecture material on basic logic gates. In lecture, students are motivated by their lab experiences to be able to construct a given logic function or truth table from a given assortment of CMOS gates. This motivates the lecture presentation of Karnaugh map reduction to generate reduced complexity logic expressions. Also at this time, the lecture material motivates the need for some form of digital storage based on the time scale difference between logic gates and human reactions—which leads to a discussion of flip flops.
- Flip Flops: In this lab students experiment with D flip flops. One of the circuits they construct is a "deglitching" circuit for push button switches which was motivated by their experience with switch bounce found in the previous lab exercise. This lab work

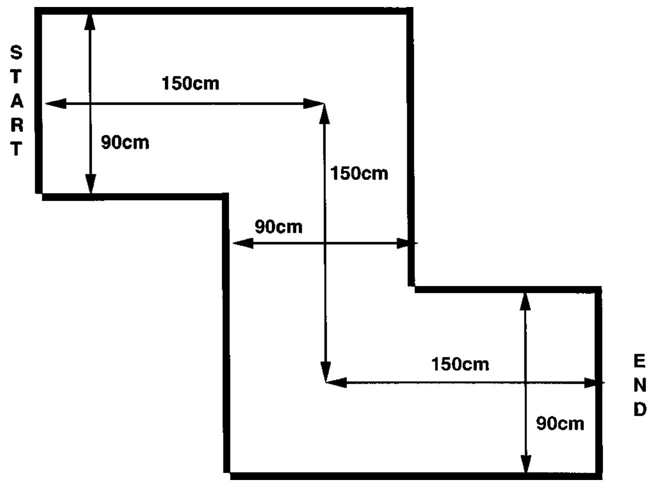

Fig. 3. A diagram of the maze used in the programmable mobile robot competition.

supports the lecture development of more general flip-flop-based circuits such as memories, shift registers, and counters.

- Memory System: In this lab students experiment with the robot's memory system which consists of a 128 × 4 SRAM and a counter to generate sequential addresses. A resettable counter controls the address lines. This material provides experiences that support the presentations on RAM and counters in lecture. This lab work supports the lecture development of the general notion of finite state machines.
- Programming the Robot: In this lab students experiment with their robots. They program them to walk through a maze. They characterize the nonidealities of the robot.
- The Robot Competition: The finale of the laboratory exercises is a competition between the students' robots. The enthusiasm of the students is increased by the donation of small cash prizes by local companies. We have found that several companies in the Pittsburgh area have been willing to fund these cash prizes. In general, robots are categorized as either "stock" or "modified" robots. Stock robots are ones that are implemented exactly as described in the robot assembly manual [13]. Modified robots have appeared in a wild range of sizes and shapes. This is an opportunity for the most creative students to really demonstrate their abilities. For example, one group of students had a robot with 9-in wheels and huge camera batteries. The actual competition is implemented as a double elimination runoff between pairs of robots. One robot starts at each end of a symmetric maze, shown in Fig. 3. The winner is the robot that exits its opponent's end of the maze first. Note, in cases where neither robot exits the maze, the robot closest to its opponent's end of the maze is declared the winner. We have seen many fascinating strategies, especially in the modified robots category, aimed at sabotaging the opposing robot. Note, robots in the stock and modified categories compete in two completely separate competitions, each with its own prizes.

One practical issue in running this course is obtaining a reliable supply of robot kits. Although it is possible for a university to create its own robot kit using standard parts, the mechanical components are generally difficult to obtain. In 1991, we started out using a robot kit distributed by Graymark International [13] that was manufactured in Japan. We selected this kit because it contained most of the components with which we wanted to familiarize the students. We then developed the entire series of laboratory exercises around that robot. The laboratory portion of the course proceeded well for the first year with a steady improvement in the lab exercise notes as we discovered various errors in the originals. However, after we had been using this kit in the course for one year, our Graymark representative informed us that the particular Robot kit we were using had been discontinued in favor of a new, much better, model. Unfortunately, what was much better about the newer model was that it used a much higher level of integration (i.e., a microprocessor)—which allowed it to achieve much more functionality. This change made it completely useless for our purposes as many of the elements we wished to have students study were now encapsulated and inaccessible inside of an integrated circuit. Fortunately, Graymark realized that more functionality was not the only reason for choosing a robot kit. They licensed the old design from the Japanese company, improved it, and have been manufacturing and selling it themselves ever since [13].

E. The GPS Navigation Lab

Approximately three years ago, a committee within the ECE Department at CMU was exploring various ways to incorporate wireless communications topics into a variety of the departmental course offerings. At about the same time, GPS navigation and positioning was becoming widespread and low in cost. It occurred to us that adding an element of communications technology to the freshman "Introduction to ECE" course would expose students at an early stage to ideas in the wireless communications area and that this might spark a later interest in these topics. It was also expected that students would be attracted to this lab course because of the visibility that GPS navigation has attained with its utilization in automobiles, boats, and even golf carts. This technology is now becoming even more ubiquitous, with GPS appearing in cell phones and wristwatches.

In order to exploit as much of the existing lecture and laboratory structure of the course as possible, we decided to consider methods of building a GPS receiver that paralleled, as much as possible, the material in the lectures and that used most of the component types used in the robot. Since GPS is a 1575-MHz service, this presented numerous hardware challenges. The approach we selected was to purchasing complete GPS RF "engines" that could be interfaced with lab and laptop computers. This has proven to be a simple and dependable approach for handling the high frequency signals. In the set of laboratory exercises,

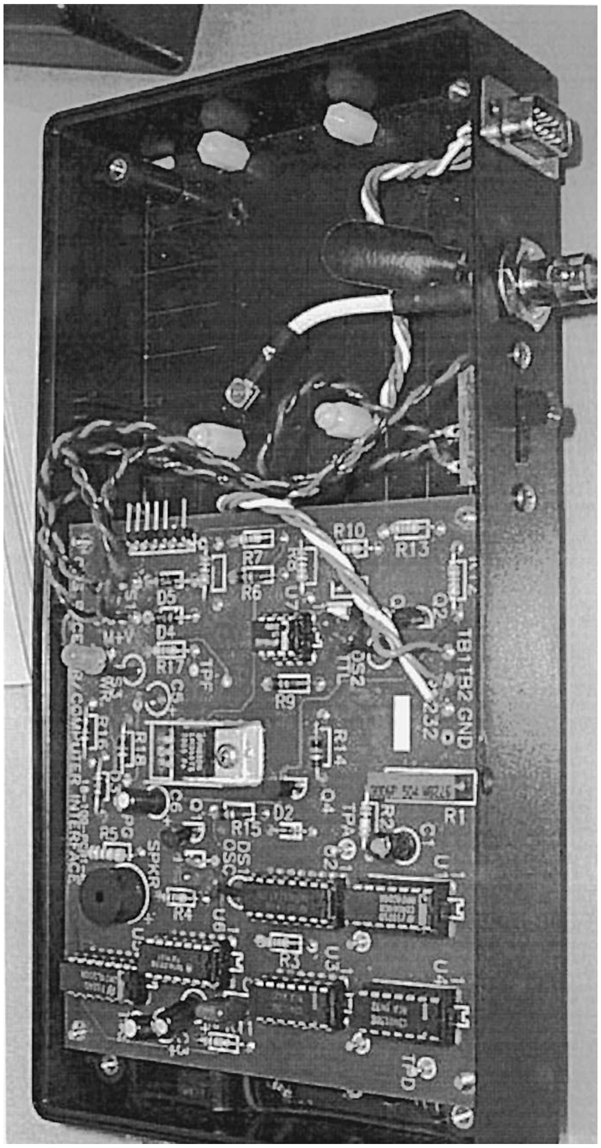

Fig. 4. Photograph of the student-built interface board used in the GPS laboratory exercises. The space at the top holds a 9-V battery and the commercial GPS RF engine.

students build an "interface board" (see Fig. 4) which level shifts the transistor–transmitter logic (TTL) output of the GPS engine to RS-232 (the signalling convention used by computer serial interfaces) and contains various other support functions such as voltage regulators, audible and visible indicators, and a clock oscillator. These support functions were intentionally designed to be very similar to the circuits in the programmable mobile robot so that the GPS laboratory exercises would provide the student with essentially the same laboratory experience as the programmable robot laboratory exercises did. In fact, we were so successful that we have been able to run the course with one set of lectures for all of the students, but two sets of lab groups—one building robot kits and one building GPS receivers. The material sequence and coverage of the GPS laboratory exercises has been adjusted to perfectly match that of the robot kit laboratory exercises. As can be seen in Fig. 5, the overall block diagram of the GPS interface board contains most of the same functional blocks as the robot control board.

One of the mobile robot functions that was not included in the GPS receiver was the motor driver. We replaced this material with background material on satellite navigation, radio signals, and computer interface connections and standards. This is similar to the approach we took with capacitors in the robot laboratory exercises. We insert supplemental material that the students need to understand what they are doing in the laboratory. Because they do not have all of the background needed to fully understand this material, we present it in a superficial way. Also, we do not hold the students responsible for this material on any of the tests associated with the course. It is this general approach of providing a superficial overview of any topics needed in the laboratory that are outside of the students' background that makes it possible to pick a number of different complex electronic systems as the laboratory vehicle.

The GPS laboratory exercises does not require the use of any laboratory equipment beyond the basic instruments used in the robot laboratory exercises. However, several additional pieces of equipment were needed. First, the laboratory classroom is equipped with outdoor GPS antennas and signal distribution wiring so that students can test their GPS receivers at their lab benches without having to hook up an antenna. Second, since the goal of the GPS receiver laboratory is to generate an output that can be sent to a computer via RS-232, each of the lab groups (we have two students per lab group) will need a mobile computer. We have used several laptop models but the software is a simple Windows package that easily fits on even a small hard drive. Most recently we have used a Toshiba Libretto, which is more of a palmtop than a laptop computer. Further effort in this area may allow us to use a Palm Pilot or similar devices which support standard GPS data streams.

One final equipment purchase was a number of commercial hand-held GPS receivers (Magellan Pioneer models) so that the students could experience actual GPS navigation long before they managed to get their own receivers built. This also adds an element of fun to the first lab sessions since student teams need to go outdoors and obtain satellite navigation fixes and perform simple navigation calculations such as coordinate conversion and distance measurement. The student-built units include a box that holds the interface board, the GPS engine, and the batteries. An external antenna and a laptop with RS-232 cable are also required.

All of the laboratory exercises in the GPS lab are essentially the same as those in the robot lab until the motor driver circuit, which is replaced by the TTL to RS-232 level shifter circuit in the GPS lab. Another obvious difference is at the end of the series of laboratory exercises. In the GPS lab students will be testing and troubleshooting receivers. As already mentioned, this is facilitated by equipping the lab with several antennas on simple window masts to allow reception of actual satellite signals without leaving the lab bench. Students are always anxious to track their first satellites, and several students requested permission to take their receivers

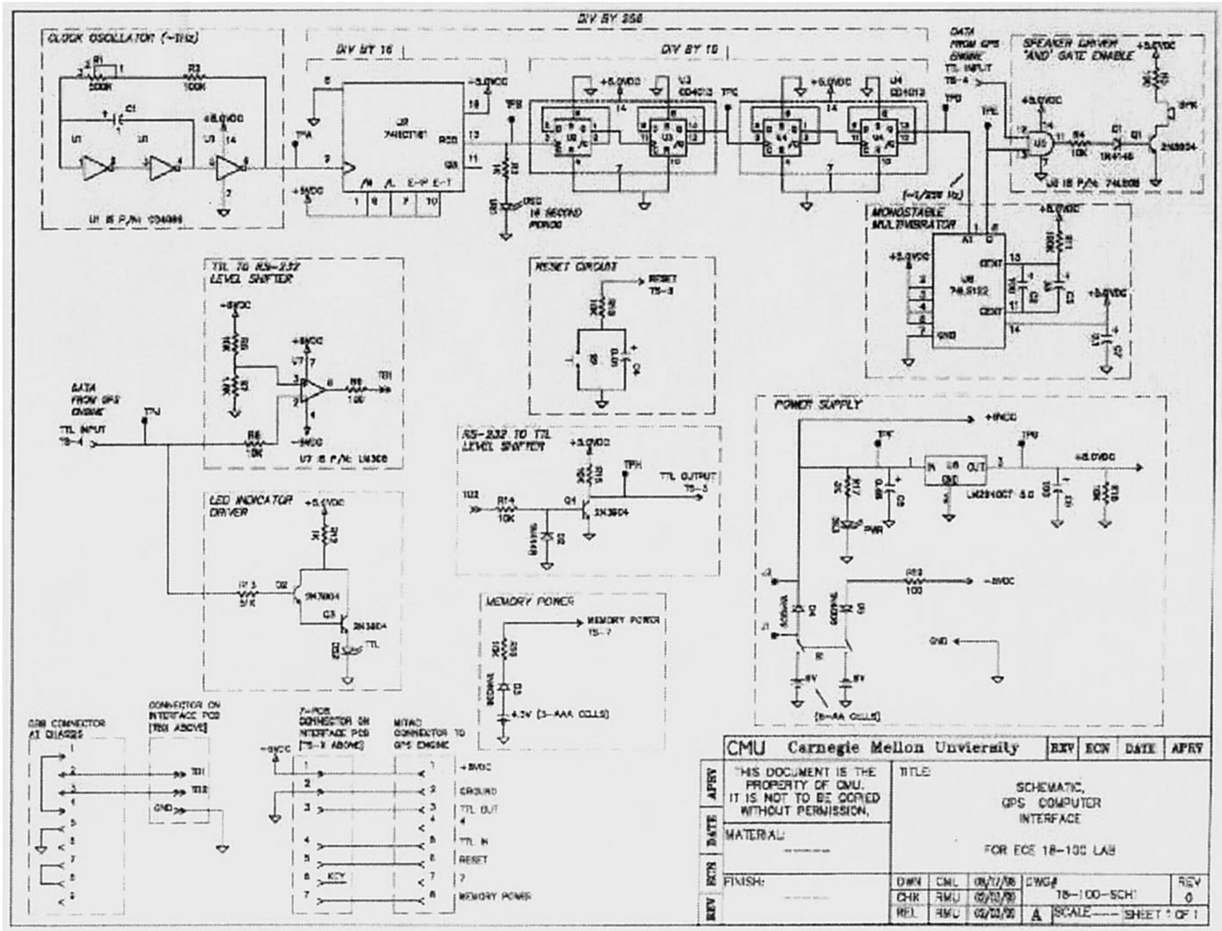

Fig. 5. Block diagram and schematic of the student-built interface board for the GPS laboratory exercises.

home during breaks to show family members and to allow additional navigation experience.

While purchasing GPS engines and antennas (which total more than $100 per system) has a higher initial cost than the robot, the completed units remain university property and all expensive hardware, including the engines, antennas, boxes, battery clips and cables, are salvaged for reuse. Only the student-built board is discarded and this assembly has a total cost of less that $20. This results in a new lab design with low per-student and per-semester costs. GPS engines have shown to be hardy devices, which is not surprising since they are designed for automobile and other harsh environments.

GPS hardware and software continue to decline in cost, and it is expected that new software packages will allow us to further enhance the interaction of the laptop/GPS receiver combination. The laptops may also play additional roles in teaching course material as new software is installed. The lab is already equipped with networked machines and many useful GPS links are bookmarked for students, including a full online GPS tutorial that is required student reading, links to the GPS hardware vendors, and government GPS reports.

In keeping with the course tradition of having a student competition (including cash prizes offered by local technology companies), student teams are given a list of coordinates for sites on campus. At each correct site a clue is posted that is used in a final puzzle or problem. The first team successfully completing the course and problem wins the top prize. There are numerous techniques to efficient outdoor GPS navigation, such as trying to maintain full-time satellite lock even when walking quickly to an estimated site location, that teams with the most experience and most reliable receivers develop. The competition last semester had schematic symbols posted at many locations, only a few of which were the correct sites. Student teams had to find the correct symbols, return to lab and assemble a simple light-emitting diode (LED) circuit. Fortunately the weather cooperated and the competition went well, but we also had an indoor navigation challenge planned using antenna masts protruding from several windows to allow GPS signal reception while remaining indoors if the weather was inclement.

F. The Search for a Textbook

In the process of creating our “Introduction to ECE” course, we encountered a number of difficulties. One of the most trying difficulties early in the process of developing the course was the choice of a textbook. Given the very specific set of topics that we selected for inclusion in our introductory course, it is no surprise that we could not find a textbook that covered exactly the topics we selected in the order we chose to cover them. As we explored the available introductory texts we found that many were specific to either EE or CE, and we did not want to force freshmen to have to buy two textbooks for this course. Of the introductory texts we found that covered ECE, nearly all of them assumed that students had already had differential equations and freshmen physics. We decided to select one of these texts and pick out the parts that corresponded to the set of topics that we covered in the course. However, we noted that this is not ideal as the freshmen found it somewhat confusing to pick out ten pages here and ten pages there.

During the first year, we used a textbook [4] which covered most of the topics; however, after using it we decided that the pace of this textbook was too fast for the freshmen. For example, one cannot expect freshmen to read a brief presentation of nodal analysis theory and to then be ready to apply it to real-world circuits. In fact, we found that it is necessary to present students with examples of how to identify the nodes in a circuit in addition to teaching them the mechanical procedure for creating nodal analysis equations. Therefore, we had to supplement the textbook extensively with lecture notes.

For the second year of the course, we switched to a textbook that had a much more thorough coverage of the CE topics included in our course [5], e.g., Karnaugh Maps and their use. Unfortunately, the coverage of the analog material in this second textbook was still too brisk for many of the freshmen. Also, the section of this second textbook on diodes and transistors took a physics-based holes and electronics approach to describing transistors. In general, the freshmen did not have the appropriate background to appreciate this presentation. Therefore, we still had to provide supplemental lecture handouts on the topics of device modeling and circuit analysis using PWL models.

In the fall of 1993, we decided that the basic circuit analysis ideas were the most challenging part of the entire course for freshmen. Therefore, we decided to switch to a textbook that covered the basic analog circuit topics in excruciating detail and with many examples [6]. This textbook had been written with the goal of being used in a course designed to provide mechanical engineering students with an overview of ECE. Therefore, many of the basic concepts in circuit analysis and digital circuit design were covered at a pace appropriate for freshmen. In this case, we had to provide supplemental lecture handouts primarily on the topics of device modeling and circuit analysis using PWL models. In addition, the section of this third textbook on digital circuit design was rather brisk for the freshmen. Therefore, we now had to provide supplemental lecture handouts on the topic of digital circuit design.

In the fall of 1995, we attempted to create a continuous set of detailed lecture handouts that not only contained the material presented in the lectures, but also contained additional example problems and supplemental material. We continued to have students buy the third textbook as a reference and did give them pages to read in it. This had the significant advantage that these course notes addressed the topics we wanted to cover, the way we wanted them addressed, in the order we wanted them covered, and without any extraneous material. Another advantage of creating our own course textbook has been that a number of different CMU ECE faculty members have been able to teach "Introduction to ECE" without an undue effort in textbook selection.

In the spring of 1996 the "Introduction to ECE" course was taught completely from the course notes which were reproduced by CMU Campus Printing. The students were not required to purchase any other text. By the fall of 1996, we were able to get both the course notes [7] and the laboratory manual [8] custom printed. In the Fall of 1997, after some new material and a number of new end-of-chapter problems were added to the textbook, a second edition was released [9], [10]. We currently plan to have the hardcover national edition of our course textbook and the robot laboratory exercise manual released early in 2000. In addition, we have developed a laboratory exercise manual for the GPS navigation version of the laboratory that should also be custom printed in the fall of 1999. A Lab Instructors Guide was also prepared for the GPS receiver laboratory and will be available by the fall of 1999 as well.

G. Helping Freshmen to Learn More Efficiently

Two strategies that we have found successful in helping students to learn more efficiently are: 1) encouraging attendance in lecture, recitation, and office hours and 2) providing an early warning to students. We have tried a number of different strategies for encouraging attendance in lectures and recitations. Having periodic lecture demonstrations has proven one way to keep students interested. Another approach is to make sure that the lectures cover the same material as the textbook; but that they use different examples to illustrate important concepts. This keeps students from concluding that they should just read the textbook instead of coming to lecture. Recitations are primarily aimed at helping students solve problems. Therefore, they tend to be very interactive. Unfortunately, many students who really need help solving problems decide to skip recitations. One approach we have tried is to give unannounced quizzes in recitation. Predictably, this is extremely unpopular with students. Another approach we have tried is to "give away" all of the tricks needed to do the homework assignments. Students quickly discover that spending an hour in recitation can take more than an hour off of the time required to do the weekly problem set.

One painful problem we have encountered regularly when teaching a freshmen introductory course is that students think they understand the material perfectly, but they are unable to solve problems on an exam. Typically these same students are so confident in their understanding of the material that they do not bother to turn in the weekly problems sets. They are shocked when they receive a bad grade on the first exam. We have found that by scheduling four to six exams throughout the course of a semester and allowing students to drop their lowest exam score we can "wake up" students to basic problems in their understanding of the course material without making them feel that they cannot

Table 1
Percent Change in CI Nonreturn Ratio from Freshmen Year to Sophomore Year Normalized to 1989

1989	1990	1991	1992	1993	1994	1995	1996
0.0 %	-6.5 %	+8.1 %	-6.5 %	-39.8 %	-30.0 %	-41.6 %	-42.5 %

make up for their bad start. In order to increase the effectiveness of this approach, we try to schedule the first exam fairly early in the semester. In this way, students can begin to improve their study skills early in the semester and they will not be penalized by a low grade on their first test as it can be replaced by a higher grade on a later test. For example, we have gotten students to start doing weekly problem sets, attend all recitations and lectures, take careful lecture notes, come to office hours to ask questions about any topics that are not clear, etc.

One other technique which has proved extremely effective for us is to use laboratory teaching assistants to help answer students' questions, in addition to the faculty associated with the course. Recruiting the best possible laboratory teaching assistants for an introductory freshmen course is critical for success in the laboratory exercises. These teaching assistants must be incredibly patient and persistent at answering the barrage of questions launched by the typical group of freshmen engineering students. We have found that because of their three hours of contact per week in the laboratory session, students develop a significant rapport with their laboratory teaching assistants. This means that the students are more willing to ask "dumb" questions of their laboratory teaching assistant than of a faculty member. For this reason, we have all of our laboratory teaching assistants schedule office hours for the students to come to them with questions.

IV. Summary and Conclusions

In this paper we presented some of our philosophy and experiences related to teaching an introductory course in ECE to freshmen engineering students. Hopefully, our description of the "introduction to ECE" course as taught at CMU clearly demonstrates that by carefully selecting topics it is possible to teach an intellectually substantive course to entering freshmen without making any assumptions about their background beyond simple algebra and high school physics. In summary, the focal points of our approach include: providing information in an experiential context; focusing on hierarchical decomposition as an approach to understanding complex systems; and modeling nonlinear circuit elements using PWL models. The experiential context is provided by having students carry out a series of laboratory exercises involving a stimulating real-world electronic system. To date, we have developed laboratories exercises around a programmable robot and a GPS receiver.

One of the motivations for creating the introductory course was to give freshmen an exposure to engineering, with the hope that this would reduce fraction of freshmen who do not return to engineering at the end of their freshmen year. Because freshmen in engineering at CMU do not designate a major until the end of their freshman year, we cannot measure the nonreturn ratio for ECE freshmen. However, we can look at the nonreturn ratio for all engineering freshmen before and after the creation of the freshmen introductory course (see Table 1). These data must be interpreted with caution as many other things could have been changing besides the creation of the freshmen "Introduction to ECE" course. In fact, we note that in 1991, the year we first started the "Introduction to ECE" course, the nonreturn ratio reached its highest value during the entire period studied. However, it is also true that the course "Introduction to ECE" was steadily improving from 1991 to 1992, while it reached maturity in 1993. Just comparing 1993–1996 with the preintroductory course period of 1989–1990, we see more than a 30% drop in the nonreturn ratio for freshmen engineering students.

Another measure of the success of "Introduction to ECE" is its popularity with engineering students and even with computer science students. The population of students who wish to take this course is so large that we offer it in both the fall and spring semesters. We are limited by laboratory resources to having 150–180 students in each semester. We have even offered the introductory course in the summer semester on a regular basis. All of the roughly 350–400 entering engineering freshmen are required to take two of the six introductory courses offered by the various engineering departments. We find that almost over 80% of the entering engineering students elect to take "Introduction to ECE." Even more noteworthy, we typically have a number of students from outside the College of Engineering, predominantly from the School of Computer Science and the Mellon College of Science, who take "Introduction to ECE." For example, between the fall semester of 1998 and the spring semester of 1999, we had 56 non-CIT students out of the 310 students who took "Introduction to ECE." This clearly indicates that structuring the course around an interesting complex electronic systems such as the programmable robot or the GPS navigation system makes it very appealing to both freshmen engineering students and students from other colleges as well.

An important question is whether the course "Introduction to ECE," as developed at CMU, would be appropriate for other institutions. Because it was intended for students with only a high school algebra and physics background, we expect that this course should be widely applicable at most colleges and universities. In fact, this course should also be appropriate as an advanced elective at some high schools, and we have successfully offered summer versions of this course to high school students entering their senior year for several years now. We have had faculty at several institutions adapt the course. For example, at Oregon State University (OSU), a large public university, this course was adopted in a form quite similar to that taught at CMU by Professor D. Allstot in the spring of 1997. The freshman nonreturn ratio at OSU has improved substantially since 1997 [14], although it is not possible to state whether or not this improvement was a result of the new "Introduction to ECE" course or not. However, the faculty at OSU have continued to use substantially the same format for their "Introduction to ECE" course since 1997, even though Professor Allstot is no longer on their faculty. In addition, faculty at OSU have indicated that some advanced high school students occasionally took the freshman "Introduction to ECE" course and did quite well. The preparedness of high school students is further supported by the success we have had at CMU teaching "Introduction to ECE" course over the summer to new incoming students (i.e., before they have even started the rest of their freshmen curriculum). Although these observations offer only anecdotal evidence, they indicate that there is a strong potential for the type of "Introduction to ECE" course described in this paper to have a wide appeal across many different types of educational institutions.

In summary, teaching "Introduction to ECE" to freshmen has been a tremendous success. It has become the cornerstone of the highly successful new ECE curriculum [11]. In general, students find the course challenging, but very exciting and interesting. Every year nearly all entering engineering students and many students from other colleges take this course. We believe that this type of intellectually substantial introductory course in ECE will become widespread in the coming decade.

V. For More Information

For an online discussion of this special issue, please visit the discussion website at http://ieee.research.umich.edu.

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