

# TEACHING CIRCUITS AND ELECTRONICS TO FIRST-YEAR STUDENTS

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## ABSTRACT

**This paper discusses the philosophy, implementation, and results of an experimental course in circuits and electronics, which is offered to first-year students at Columbia University. The course includes a strong laboratory component. The results, which are reported, have been excellent.**

## 1. INTRODUCTION

Like many colleagues at numerous electrical engineering departments, several years ago the Department of Electrical Engineering (EE) at Columbia University became concerned about the failure of the traditional electrical engineering curriculum to adopt to the changing times [1-5], and in particular to the new generations of students [1,3,5]. The department's curriculum committee undertook to look into alternatives and come up with a new curriculum. It soon became obvious to us that the recent trend to start students in electrical engineering in their first year [2,3] had a lot going for it, and decided to create an appropriate first-year course. This paper reports on the results of this undertaking.

## 2. CONSIDERATIONS IN DEVELOPING A FIRST-YEAR COURSE

In developing our first-year course, we had to take several considerations into account:

**1. Today's students are different.** They differ from those of older generations in at least two respects [1,5]: They have not tinkered, and thus, if started in EE through theory, have no idea where, in practice, all this fits or why it is useful. Second, they are impatient; they are used to immediate gratification (exemplified by their obsessive playing of computer games, where they push a button and see "major results" right away). Telling these students that they will "see later in the curriculum" why circuit analysis is useful, does not work; two semesters down the road, or even one, is too far into the future for them. Thus they lose motivation, develop frustration and many become passive learners. To avoid this, *they need to be introduced to theory and practice in the same course.* Obviously, several possibilities offer themselves for such a course: circuits with electronics, digital signal processing, etc.

**2. Hardware? Software? Multimedia?** Today's students come to us, if not as well-developed hackers, at least with a significant familiarity with computers, and

definitely familiar with many of their uses. Psychologically, being members of the TV and computer-games generation, they relate to the computer screen extremely well. They tend to develop the impression that all that needs to be done is push buttons or, at most, write programs, and *somebody else, somewhere*, will take care of designing and building the hardware. This gets reinforced if the first engineering courses they see are software-oriented, and by the time they get to hardware design it is too late to relate to it. We thus end up with huge numbers of users of computers and other hardware, but hardly enough people to design such hardware. (One wonders, if this trend continues, what will the software of the future run on?) To limit the magnitude of this problem, one should make sure that students get exposed to real hardware as early as possible; in this way, they will at least get a chance to see how they relate to it. Thus, courses in which the student's point of contact with (hidden) hardware is, yet again, the keyboard, are not good candidates for first electrical engineering courses, whether they deal with multimedia, or signal processing, or simulation, etc. *What is needed is a course with real contact to the real world, using a real (not a virtual) laboratory.*

**3. Tying the first course to the rest of the curriculum.** In today's crowded curriculum, there is hardly room for adding yet another required course, unless it can be tied well to the rest of the curriculum. Possibly, a later course in the curriculum may have to be eliminated, to make the introduction of a first-year course possible. Thus one needs to make sure that the first course, in addition to providing motivation, gives real knowledge to the students. In our case, this ruled out a broad overview course. The first course should also be such that, at least for some time, it can coexist with existing courses, such as traditional courses in circuit analysis and electronics, in a harmonious way. If a curriculum revision is intended, this approach allows a gradual, careful transition to the new curriculum.

## 3. THE CHOICE OF CIRCUITS AND ELECTRONICS

The above considerations, taken together, strongly pointed to circuits and electronics as an appropriate subject for the first-year EE course. Such courses have been offered for several years in many schools, including UC Berkeley, MIT, and the University of Illinois at Urbana-Champaign. Electric circuits are an excellent vehicle for introducing several general concepts, and electronics is the best way to demonstrate the utility of those concepts to

newcomers. Electronics also allows for experimentation with real hardware, as opposed to using a computer and its interface yet again. What is learned in such a course shows to the students the utility of the mathematics courses they have begun to take, and can greatly motivate the study of other subjects, such as signal processing, control systems, and computer hardware design. The course is obviously an asset to the students if they later take more advanced circuits or electronics courses. The course can be designed in such a way that it does not “de-throne” such courses; however, it certainly feeds well-prepared students to them, who have touched and felt real circuits, and are eager for more.

For all the above reasons, the curriculum committee of our department decided to create a first-year course entitled *Introduction to Electrical Engineering*, dealing with circuits and electronics. This author undertook to develop such a course in 1996, and was exempt of teaching duties in order to prepare it. The rest of this paper is devoted to describing this course in detail, and discussing the results we have seen so far.

#### 4. GUIDELINES FOR DESIGNING THE COURSE

The course was designed based on the following guidelines:

**1. Theory and applications should be taught in parallel.** The applications demonstrate the utility of the theory, and motivate its further study.

**2. No computer simulation.** Students need to concentrate on understanding a significant number of new concepts, and they need to touch and feel the devices that embody such concepts. This process should not be obstructed by the syntax, manuals, and idiosyncracies of simulators. Also, students often tend to use simulation as a substitute for thinking, which is the worst that can happen when the basics are laid down. This author has never allowed simulation in beginning courses, and has noticed that, even in more advanced courses, where he introduces simulation to advantage, students tend to stop and think mainly when the computer is down. It is interesting that views against using simulation in basic courses have been expressed by a circuit simulation pioneer [1]. So, let students simulate at a later stage, when they know what it is they are simulating. *Reality before virtual reality.*

**3. Only time domain.** Obviously, to accommodate a significant amount of electronics in the course, some circuit analysis topics have to be postponed for a later course. We find that the frequency domain is one such topic. After all, at this level, the frequency domain is also a form of virtual reality. We live in the time domain, and we should make our first connections to the subject matter in that domain. It is not a good idea to have students blindly manipulating phasors before they have even observed time waveforms with an oscilloscope. Important concepts, such as frequency response, can and should be introduced in the time domain.

**4. No formalized, systematic analysis techniques.** At this level, *systematic* can mean *blind*. Students in this course should learn how to look at a simple circuit and try to apply Kirchoff’s current and/or volt-

age law to it in a clever way to get what they want, just like practicing engineers often do. They are not motivated, though, to learn how to blindly solve a circuit with  $n$  meshes, where  $n$  is arbitrary, because they have no use for such a circuit. As the students’ familiarity with electronic circuits progresses, and as the circuits they see become more sophisticated, they eventually see themselves the need for general techniques, and this motivates them for taking a subsequent course on formal circuit analysis. You can then be sure that they will do much better in such a course, than they would otherwise.

**5. No digital before analog.** Circuits laws cannot be introduced adequately if we insist on focusing on just two levels. In addition, we should not give in to the hype, propagated by the media, about the “digital world”. The real world needs analog interfaces, which are increasingly difficult to design; as a friend of the author once said, the need for analog may go away one day, if they get us to swallow the microphones. Many chips are now mixed analog-digital, and even *digital* chips handle non-digital waveforms inside. Two-level waveforms exist only on the pages of textbook; ask any designer of high-speed micro-computer chips, and they will tell you how much analog design is needed to make high performance possible. The author has had the opportunity to say much more about these issues elsewhere [6].

**6. Links to other courses should be provided.** These help to give a perspective, and to motivate the study of other courses (e.g., computer design, circuit theory, semiconductor devices, or communications).

#### 5. CONTENTS

Based on the above guidelines, the contents of the course were chosen as follows:

- Charge, current, voltage, and power
- Kirchoff’s laws
- Independent voltage and current sources
- Resistors and combinations of resistors
- Simple resistive circuits and their analysis
- Linearity and superposition
- Thevenin and Norton forms
- Op amps
- Comparators
- Amplifiers implemented with op amps
- Capacitors and inductors
- First-order RC and RL circuits
- Diodes
- Rectifiers, limiters
- Transistors (bipolar and MOS)
- Single-transistor inverters
- Modulation, demodulation, and radio reception
- Logic functions and logic gates
- Flip flops, counters, and registers

Most textbooks used for introducing non-majors to electrical engineering can be used to cover most of the above topics, possibly supplemented with a couple of short write-ups prepared by the instructor.

## 6. LABORATORY

For the laboratory we considered several options, including some that are being tried elsewhere. We found that, for our purposes, it is best at this level to keep the experiments independent (as opposed to their being part of a larger construction project). In this way we have great flexibility in designing the experiments, in order to reinforce certain important concepts. Also, in this way we can introduce design projects early, and have students see results right away. In other words, we found that the lab format that works best for us is a mixture of the classical and the modern approaches. The laboratory experiments come, mostly, right after the corresponding theory is covered. Students have up to 3 hours to complete each experiment, and they are asked to submit a very informal, one to two page report before they leave the lab. The following is a list of experiments:

- Basic dc circuits and measurements
- More dc circuits and measurements
- Time-varying signals
- Op amps—basic characteristics
- Amplifier design using op amps
- Design project
- Resistor-capacitor circuits
- Diodes and their applications
- LC circuits
- Modulation and demodulation
- Radio receiver design
- Transistors
- Digital logic circuits
- Final design project

The final design projects were chosen by the students from a list of suggested projects, which included audio mixers, square-wave generators, motor-activating circuits, digital counters, analog-to-digital converters, sirens, a photophone, etc. In addition to the two lab periods devoted exclusively to design, there are design parts in several of the other lab periods.

**A touch-and-feel approach:** The experiments were designed to help the student develop intuition and relate, as much as possible, what is learned or measured to what is perceived through one's senses. For example, in the third experiment, which deals with time-varying waveforms, the students are introduced to the function generator and the oscilloscope. Through an amplifier and loudspeaker, they get to hear the waveforms they observe on the scope's screen, and through a microphone they observe the waveform of their voice, whistling, or clapping. Then the *touch-and-feel* approach goes further. Here is an excerpt from the instructions from that experiment:

*Remove carefully the speaker's panel. Touch the paper cone of the speaker very lightly, and feel its vibration for various frequencies and amplitudes. Then, lay the speaker flat, with the paper cone facing the ceiling. Place a very small particle (e.g., a grain of rice) on the cone, and observe its movement when the frequency of the signal is low (a few tens of Hz). Then remove the particle, replace the speaker panel, and set the speaker upright.*

The above may sound like an exaggeration, but the author knows, from his early start as a hobbyist/experimenter, that such experiences stay in memory, and help make things *click*. They provide the confirmation that what is done in the lab is real, and that the student can relate to it. This removes stumbling blocks, increases intuition, and motivates further study.

**Lab equipment:** The simplest possible lab equipment was chosen. The reason for this is similar to that given above for not using computer simulation in this course. In the lab, students need to concentrate on the essence of what they are measuring, on the essence of a basic principle or physical phenomenon they are trying to verify. This process should not be obstructed by instruction manuals, instruments with myriads of features, menus and submenus, etc.; the simplest instruments have features which are sufficient for what needs to be measured or observed at this level, and they cost less, too. Instruments should be the means, not the end. There is time for instrument sophistication later.

Special plexiglass boards, each with several basic components and leads attached to them, had to be constructed for use in the first few experiments, for making all connections visible. After the students feel comfortable with making circuit connections, the ubiquitous white prototyping boards are used. Simple 1-W power amplifiers were also constructed by the EE Department's electronics shop and were used as part of the on-bench equipment. These, as well as the microphones, had to be electrically fool-proofed to make them able to withstand abuse on the part of beginning students.

**Evaluation and fine-tuning of the experiments:** At the conclusion of each lab session, each student was asked to fill in a questionnaire evaluating the experiment in terms of the clarity of the instructions, how interesting the experiment was, how much the student learned by doing it, whether or not the student's background was adequate for doing the experiment, and whether the time allowed for doing it was sufficient. The questionnaire also asked the students to list the points that presented difficulty for them, and to give suggestions for improvements. After trying the first version of the lab instructions on three lab sections (24 students per section), they were extensively revised in the following year, and tried on another four sections, asking again the students for an evaluation. A marked decrease of the number of points of difficulty listed, and of the number of suggestions, was noted the second time.

## 7. RESULTS

The course was offered for the first time in the 1996-97 academic year. It has met with success beyond our expectations. Some statistics, from the first year the course was offered, follow.

Before the introduction of the first-year course, the beginning EE course used to be a traditional linear circuits analysis course, and students had the option to take it in the sophomore or junior year. About 25% used to choose to take it as sophomores. The year after the first-year course was offered, the circuits analysis course was maintained, and the students were still given the above option (at least, in the transition period to the new curriculum). The percentage of sophomores in this course went up to 48% this time, and the actual number of sophomores in it nearly tripled, consisting mostly of students who had taken the first course; apparently, having had their first taste of EE, these students did not want to wait.

The linear circuits analysis class mentioned above still accepts, for now, students who have not taken the first-year course, and teaches analysis techniques *from scratch*, at a higher level than the first-year course. Yet, those in it who had taken the first-year course, in comparison to those who had not taken it, achieved an average final grade of 0.65 points higher (with 4.00 corresponding to maximum grade). The author attributes this to the intuition which the first course imparted on those who took it; intuition makes theories "click".

The ratings given by the students on the lab experiment questionnaires the first year the course was offered, were averaged over all experiments. The students gave an average score of 4.38 (with a maximum possible being 5) when asked how interesting the experiments were, and a 4.29 when asked how much they had learned from the experiments. Not surprisingly, the experiments that the students scored highest were the design projects!

In the course evaluation conducted by the students, and administered by the Engineering Dean's Office, the students who took the course the first time it was offered gave it a score of 4.61 on a scale from 1 to 5. The students' comments, collected and communicated to the EE department by the Dean's Office, were extremely positive and included "Excellent course", "Thank you for this great experience", "Lab very useful", "Every department should have a class like this", "I learned a lot and feel prepared for the rest of my major", "Labs were great—very helpful in understanding the material", etc. In the following academic year, and with the encouragement of the dean, most other engineering departments at Columbia started first-year courses as well.

## 8. CONCLUSIONS

There is no question in the mind of this author that the classical way of getting students started in electrical engineering no longer works. Students are too different today, for a forty-year-old approach to work on them. After much studying of alternatives, including those being tried out elsewhere, we came up with the conclusion that circuits and electronics, with a real lab and nothing virtual in it, is the best way to introduce students to electrical en-

gineering, and indeed in their first year. We went ahead and tried it. The results exceeded our highest expectations, and we strongly recommend this approach to our colleagues. This approach can work equally well for starting students in the second year. Some indicative performance statistics have been given above. Of course, these, like most statistics, are subject to interpretation. To this instructor, the most unambiguous indication of success was seeing the students' face light up when their designs worked for the first time, and hearing students say that this course made them realize that EE is for them.

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## REFERENCES

- [1] R. A. Rohrer, "Taking circuits seriously", *IEEE Circuits and Devices*, vol. 6, no. 4, pp. 27-31, July 1990.
- [2] J. A. Orr and B. A. Eisenstein, "Summary of innovations in electrical engineering curricula", *IEEE Trans. Education*, vol. 37, pp. 131-135, May 1994.
- [3] S. W. Director, P. K. Khosla, R. A. Rohrer, and R. Rutenbar, "Reengineering the curriculum", *Proc. IEEE*, vol. 83, pp. 1246-1269, Sept. 1995.
- [4] J. Choma, "Vision, goals and tasks", message to CAS officers, Dec. 31, 1996.
- [5] Y. Tsividis, "Some thoughts on introducing today's students to electrical engineering", accepted for publication in *Circuits and Systems Society Newsletter*, vol. 9, March 1998.
- [6] See pp. 1-10 in Y. Tsividis, *Mixed Analog-Digital Devices and Technology - An Introduction*, McGraw-Hill, New York, 1996.