OUTSIDE-IN ELECTRICAL ENGINEERING INSTRUCTION FOR NON-EE MAJORS

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It would seem that there is no question about the proper order in which to learn things. One must crawl before he can walk. One must learn arithmetic before algebra. One must learn about semiconductor junctions before common emitter amplifiers. All these are so obvious that they are not worth discussing—except the last one! We propose that electrical engineering instruction for non-majors can be greatly improved by taking up many topics in reverse of the usual order.

The title of this paper refers to the proposed approach as "Outside-In Electrical Engineering Instruction". This "outside-in" or "top-down" thinking is widely applicable and is practiced in many fields—especially by engineers.

When an engineer designs a communications system, he or she begins with the broad goal to be accomplished, then blocks out the main functions, and then at last, after all that preliminary work, gets down to the details. Figure 1 illustrates some of this standard approach. We observe carefully that the engineer does not begin with transistors or even ICs themselves and build up his design ideas from there. No, he first thinks out the broad system blocks, deriving them from the overall mission. Then he gradually moves down a level at a time until he has wrapped up all the details. At some point he may decide to leave the remaining details to someone else, but the design always continues with the same outside-in approach.

But contrast that with what happens when the system has been designed and is to be built. Now the engineers start at the lowest level, put transistors and IC's together, assemble these into component devices, assemble the components into subsystems, and arrange these into the final system which does the job needed.

The question to be addressed in this paper is simply: In teaching EE to non-majors which of these two approaches is best? Our thesis is that topics should be taken up in the first order—an order that follows the engineering design procedure—an order that starts with the broad uses and system components and only then delves further down into such details as transistors and solid state.

In examining the presently-available textbooks and in discussing presently taught courses, it would appear that most instruction instead follows an inside-out approach. We think there is a real opportunity here for great improvement in minor instruction by following an outside-in approach.

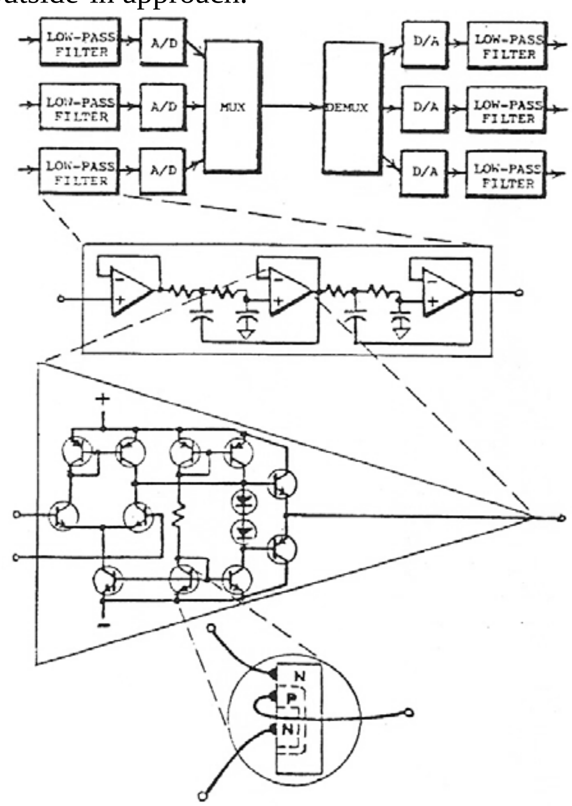

Fig. 1. A communication system showing structure of nested levels.

Some Examples of Outside-In Thinking

The outside-in approach is not new nor radical; it is used consciously or unconsciously in many other fields. We cite a few examples to suggest the advantages of the approach.

A revolution in computer programming has recently taken place. Instead of attempting to build these programs up from detailed elements, a "structured procedure" is invoked in which a sequence of broad tasks is established—tasks that call on specific details which have not yet been designed. Following this the detailed sections of the program are designed in such a way as to fit into the previously established overall structure. This procedure is called "top-down" programming.

Cookbooks are often organized, at least in part, with "outside-in" structure. For example on page 795 of "The Joy of Cooking" by Rombauer[1] you will find a dinner menu that includes ham loaf. The recipe for ham loaf on page 147 includes mushroom sauce. The recipe for mushroom sauce on page 386 includes brown sauce.

The recipe for brown sauce on page 385 includes soup stock, which has its recipe on page 50. In planning the meal you would of course start with the menu. But, just as with the building of the communication system, in preparing the meal you would of necessity start with the soup stock.

If an artist is going to do an oil painting, he first lays out the major masses with charcoal on his canvas. (see Fig. 2 taken from Schwartz[2]). With these as a reference he then goes back and fills in some smaller masses with charcoal.

When he has planned the painting in sufficient detail, he begins with the oils to realize the many details until the whole painting is complete.

As a final example of the outside-in approach, consider good newspaper writing. The first couple of paragraphs summarize the event being reported. Then each major point is taken up, followed by attention to minor details. The article sometimes dribbles on, mentioning related events or quoting speculation as to what is to come.

In all these examples there can be a considerable difference between the professional practice and the teaching of professional practice. For example, how is a person taught to cook? Does the first day in Home Ec start with menus? Hardly. The first day typically begins with a hands-on experience such as making biscuits. But it should not begin solely with measuring spoons, recipe reading, etc.

On the other hand a beginning artist is taught to make rough sketches before being taught to paint detail. Actually both these approaches are in harmony with outside-in teaching, which emphasizes student motivation.

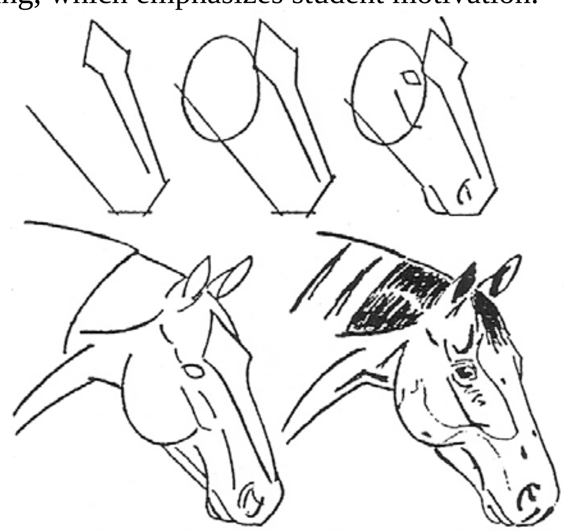

Fig.2. In planning a painting, the artist proceeds from mass structure to detail.

Advantages of an Outside-In or Top-Down Approach

Before applying outside-in thinking to the details of engineering instruction let's look at its advantages wherever applied.

Perhaps the greatest advantage of the outside-in approach is that it motivates the student. He wants to appreciate why he is putting effort into learning something. He needs a better answer than, "Because you'll need it later. You'll see how it all fits together in the end."

Mushroom sauce is valued by seeing how it spruces up a ham loaf. This appreciation is passed on to the otherwise uninteresting brown sauce because it is needed to make mushroom sauce.

Any exercise may be made interesting in and of itself, but it helps greatly to be able to see the usefulness of the exercise. This is especially true of a non-EE, who takes a course in EE as a means to an end. If the course begins with semiconductors, he may object, "They're trying to make an EE out of met" with an outside-in approach, he may eventually be led to appreciate semiconductors and want to learn about them. A system, which stands alone in providing a service to the user, is the place to begin; It meets the non-EE on common ground with systems concepts in his own major.

A related advantage of outside in instruction is that structure is provided in which to place details—or, in the common management vernacular, "You've got to have a tree to hang the balls on." Facts and ideas are learned much more rapidly if their relationship to other elements is clear. In Bruner's classic book, "The Process of Education," we are told: "If early learning is to render later learning easier, it must do so by providing a general picture in terms of which the relations between things encountered earlier and later are made as clear as possible"[3] and, "…unless detail is placed into a structured pattern, it is rapidly forgotten." [4]

An artist that sketches the major masses of his subject gets a feel for the relative size and position of the details to come. Someone untrained often begins by "working from detail to detail. He invariably finds, upon standing back to survey the completed picture, that some elements are out of proportion or out of position. similarly, an engineering student will understand why he is designing a modulator to meet certain specifications if he has first been introduced to the concept of a communications system. Otherwise, in these situations, we are tempted to say, "He can't see the forest for the trees," or, "You've got to see the big picture to understand this."

Another advantage of the outside-in order of study is that, as in a newspaper story, the study can logically stop at whatever level of detail satisfies the need at the moment. The instructor can easily vary the depth to which he carries his class from topic to topic. Students themselves can adjust their penetration in accord with their own interests and needs. This is especially true for non-EE's who, like all engineering students, are pressed for curriculum time and will not wish to go into great depth in some topics. Unlike EE's they reasonably sacrifice electrical engineering depth for breadth.

This is not to minimize the importance of detail to engineering thinking. In a very real sense detail is everything. The engineer is himself limited by what can be done with detailed parts of his equipments or analyses. He cannot afford to ignore these details. He makes his systems breakthroughs by what might appear to be small overcomings in detail limitations. But outside-in teaching doesn't limit the level of detail or give less importance. In fact detail is motivated and given enhanced status by a position near the end.

Provost F.E. Terman more than ten years ago[5] observed that, "As the amount of knowledge to be covered increases, undergraduate engineering programs will become more and more general and basic in character, and thereby progressively less satisfactory as the foundation for a professional career in engineering." Surely within an individual course or course sequence an adequate structural grounding, to provide the framework for such detail as in most important, will at least alleviate this problem. Its possibilities in the 4year curriculum as a whole are beyond the scope of the present paper.

There is a final point to make about outside-in learning. It is clear that this approach is in accord with problem solving in engineering practice, where one proceeds naturally from "the big picture" step-by-step to whatever level of detail is needed for implementation or understanding. To steep students in the kind of thinking they will employ in their professional lives is surely advantageous educational practice for their college years. Engineering design, thought, and analysis are need-driven. Good habitual thinking for students in engineering courses becomes the basis of good engineering thinking in practice. Bruner comments on this point: "…it is easier for [the schoolboy] to learn Physics behaving like a physicist than by doing something else."

On the other hand, difficulties of the more conventional inside-out. course construction and teaching, need hardly be mentioned. These troubles have been traditionally accepted as normal to minor course teaching: unmotivated students, inability of students to perceive the usefulness to their own major of material covered, a difficulty in motivating professors to teach this kind of course enthusiastically. When both student and professor think in terms of purpose and the specific relations of course elements to each other and to student major field, the work of both can be revivified.

Application to the Minor EE Course

This outside-in idea is deceptively simple. As in most aspects of engineering teaching, many complicating trade-offs arise. The most obvious difficulties have to do with language and motivation. Whatever the ordering of topics, good instructors have always made adjustments to provide for both these needs. For example the instructor says, "Before we get started on solid state ideas, let me tell you just a little bit about transistors and what they are used for," or, "That's a good question. Here's the way this idea is applied in your TV sets."

Some authors have realized this need for structure and incorporated it in their texts, for example Sedra and Smith in their new electronics book. In their preface they state: "We strongly feel that it is no longer necessary to study physical electronics prior to electronic circuits. In fact we have found the reverse sequence, that is circuits and then device physics, to be more effective." Further, this whole text starts with systems.

There are many ways to structure an outside-in minor course. Here is a possible method:

1. INTRODUCTION

1.1 Relation of EE to other major fields
1.2 Broad EE applications:
  1.21 power and
  1.22 signals
    1.221 Instrumentation systems
    1.222 Control systems
    1.223 Communications systems
    1.224 Computer systems
1.3 Circuits as a unifying characteristic of all EE

2. CIRCUIT ANALYSIS

2.1 Basic circuits (dc)
2.2 Circuit analysis (dc)
2.3 AC Circuits I—(ac phasor 60Hz)
2.4 AC Circuits II—(ac general & variable *f*)
2.5 Transients
2.6 AC Power

3. ELECTRONICS & SIGNAL APPLICATIONS

3.1 Analog instrumentation
3.2 Digital instrumentation
3.3 Feedback control
3.4 Communications
3.5 Microprocessors
3.6 Digital ICs
3.7 Operational Amplifiers
3.8 Transistors as analog devices
3.9 Diodes & transistors as switches
3.10 Semiconductors & IC Technology

4. MACHINES & POWER

4.1 Plant power systems
4.2 Transformers & magnetics
4.3 Rotating machinery basics
4.4 Motors & AC machines

A study of this one-dimensional list is aided by the two-dimensional layout of Fig. 3.

Section 1 is clearly a good beginning of an outside-in approach; it introduces the student to the major system uses of EE. A brief example of each type of system is Sufficient, and they can be described in such a way that hardly any knowledge of circuits or signals is necessary.

Section 2 at first seems to be a departure from the outside-in approach since it jumps to the circuit level. What has happened actually is that we have left the outside-in structure in order to give the student a language to discuss further levels in the structure. Inside the systems level all of EE is circuits at varying levels of detail. It becomes apparent that within EE instruction are two structures: the nested structure of physical systems, circuits, and devices that we have been addressing; and the circuit mathematics and language needed to understand the various levels of the physical structure. In Section 3 the instruction gets back to systems in greater depth, but first the student needs the circuit analysis concepts of section 2.

How much circuit math should the student be given before tackling further levels of the outside-in structure? No more than necessary! Otherwise the student loses in some degree the motivation of application. For example, the concept of poles and zeros is not needed to understand instrumentation systems; it can be introduced along with control systems.

The key is to *always maintain contact with a sense of structure and application*. This maintains the student's orientation and motivation. For example, the discussion of circuit analysis can begin with a "mini-system" such as a flashlight as a vehicle for circuit concepts. This is like starting the cooking course with a "mini-menu" of biscuits.

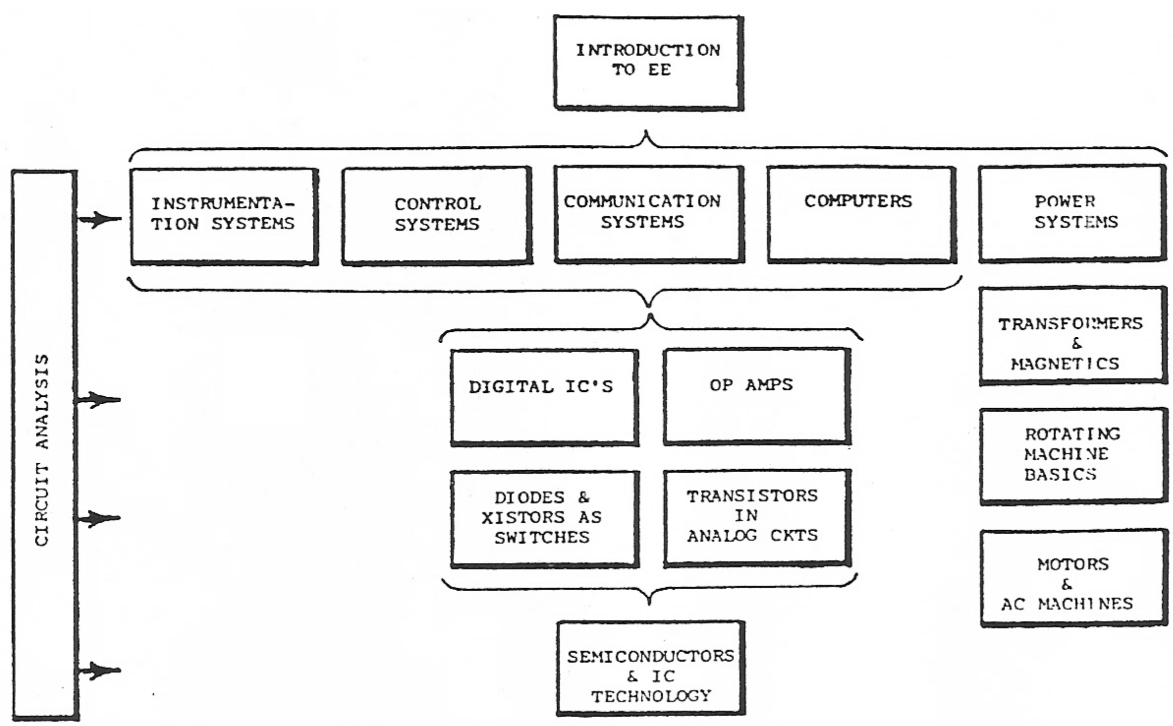

Fig 3. Topics of electrical engineering arranged according to levels of an "outside-in" approach. Note that circuit analysis is not nested but pervades the entire structure.

The first five topics of Section 3 address electronic systems in greater depth than they were given in the introduction in Section 1. The next level in the nested structure is integrated circuits—both analog and digital. These are covered next in Section 3. Then the discrete elements, transistors and diodes, are introduced, and finally a very brief presentation of semiconductor physics and IC technology.

Section 4 goes back to the top of a structure and describes power systems. The remaining topics deal with their components. Note that power systems were not presented next to the group of electronic systems. This is because power and electronics have different inner levels for the most part.

Some Objections Answered

One frequently encounters such objections to outside-in instruction as:

"A student can't thoroughly understand or intelligently use a piece of equipment until he knows what's inside."

We can only answer that each day we all use items that we don't understand the workings of. A pianist gets to know the feel of the keys without understanding the action inside. In the same way a student can learn that an FET op amp has a very small input bias current—in the picoamps—without knowing anything about transistors. What we usually do is form simple models to describe the behavior of something complex inside. These often take the form of "two-port" models. For quite a while this is good enough. Later, if the student wants to become more "expert", he learns more about what is inside.

"But he should become an 'expert' on the innards of an op amp first. Only then can he take into account all the subtleties and limitations in its application."

Subtleties are meaningless until a structure is built. This first encounter gives the student a simple structure (although a surprising depth can be achieved the first time around). A second encounter, after investigation of levels inside, would be an opportunity for even greater depth dealing with subtleties. A third encounter may even be appropriate in some cases. Bruner calls this a "spiral curriculum."[8]

"We don't have time to do anything twice. We've got to do it right the first time."

What repetition and review exist are essential in good teaching. It is false economy to dwell so briefly on the simple concepts that the student retains little. In fact a great deal of time is saved by the outside-in approach through improved motivation and Clarity.

Undesired repetition is minimal in that when it looks at the same material again, it does so from different points of view. The student probably learns the inverting configuration in his first encounter with op amp applications. Slew limiting may well be left for a second encounter. There need be little overlap.

In teaching EE to non-EE's there is an unusual opportunity to implement such a spiral curriculum. Because only one professor is in charge of the whole subject of EE, there is no difficulty in coordinating the multiple encounters with a topic.

"Outside-in teaching encourages the student to be satisfied with superficial knowledge. He may 'tune out' when the course gets to the details."

There are some pitfalls here, but it is not hard to avoid them. It is true that an outside-in approach gives the student an early ability to do some useful things. If he seems satisfied with this, he should be encouraged by example and by exam to go further. It seems unfair to generate a captive audience by giving the students pieces of a puzzle that come together only at the end of the course. It gives little credit to the instructor's ability or to the students' judgment, and it robs the students of the benefits of the outside-in approach.

Other Observations

We have found laboratory work to be an indispensable part of any course based on such an approach. It provides two major enhancements: First, minor EE courses tend to cover a great deal of ground in a short time. The laboratory adds realism and solidity to such rapid instruction. Second, students tend to enjoy laboratory work, especially as it can be related to some of their own major interests.

A perennial question is always: "should such a course be one or two semesters?" Some EE staff are horrified at the thought of attempting any such sequence of topics in one term. The most frequent suggestion we have from students who take the one-term minor course at WPI is that it should be extended into two terms. But often they will add without being asked, "But actually I wouldn't have time to take the other term with my Mechanical Engineering schedule." Their department curriculum committees want one term.

Our students are almost entirely upper classmen, sophisticated both in engineering course study and in already having considerable technical background. We believe strongly in getting them into their majors rapidly and extensively, not only as a matter of interest and motivation, but also as a practical determination of whether they really want that major. Therefore we seldom get them as minor students in their Freshman or Sophomore years.

The answer the authors prefer to the question of one term or two is that it depends on whether they are Freshman-Sophomores or Junior-Seniors. We also have found that the upper half of our minor course class can go directly into the EE Department's electronic sequence and compete effectively with the electricals.

In Summary

Minor students are particularly appreciative of instruction which is clearly geared to their needs and interests.

Any student enjoys and benefits by the motivational effects of understanding a reasonable amount of the end use and significance of what he is dealing with. Starting with how a topic or area fits into the student's future professional activities and proceeding in instruction systematically to lower levels of detail provides this understanding.

The instructor, too, is freed by such a procedure to select topics and adjust the time spent on them to suit his pedagogic needs and resources. Such a procedure enhances the instructor's ability to tailor work assignments and laboratory work even to individual students.

References:

1. Irma S Rombauer, "The Joy of Cooking" (New York, The Bobbs-Merrill Co., 1946)
2. Don Schwartz, "Horses Heads in Oils and Pastel" (Tustin, CA, Walter Foster Art Books)
3. Jerome S. Bruner, "The Process of Education" (Cambridge, Harvard U. Press, 1960, 1982 printing) p. 12.
4. Bruner, ibid, p. 24.
5. F.E. Terman, "Engineering Education in Retrospect and in Prospect" (Britannica Review of Developments in Engineering Education, Vol I, 1970) p. 7.
6. Bruner, ibid, p. 14
7. Adel S. Sedra and Kenneth C. Smith, "Micro-electronic Circuits" (New York, Holt, Reinhart and Winston, 1982)
8. Bruner, ibid, p. 52.