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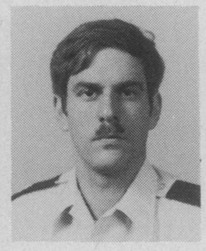

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What to Teach: Understanding, Designing, and Revising the Curriculum

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Abstract—A systematic procedure for curriculum design is briefly summarized, and the crucial step of content selection is then discussed in detail. The content is described in terms of the domain, principles, and problems of the discipline, and some suggestions regarding the teaching of each are made. The various reasons for curriculum revision are listed, with particular emphasis on the ways of solving the dilemma posed by the fact that time devoted to learning cannot increase in proportion to knowledge itself.

I. INTRODUCTION

BROADLY used, the term "curriculum" refers to a systematic group or sequence of courses or educational experiences that is either offered or prescribed by a school or under a program, or that is required for graduation, certification, or as a preparation in a field, trade, or profession. The task of designing a curriculum deserves a great deal of careful thought because the effectiveness and outcome of education are critically dependent on it. It is also a difficult and time-consuming task because it must deal with such basic issues as the goals of education, and with the conflicting requirements of perpetuation and change. Few discussions and case histories of curriculum design are available in the literature of engineering education [1]-[3].

Ideally, the design of a curriculum proceeds through the four major steps outlined in Fig. 1, leading to a curriculum which consists of a set of courses. A "course" is a useful basic unit with which to construct the curriculum because: 1) it deals with a single, or narrowly defined, subject matter; 2) it represents a learning effort of a few weeks (full-time equivalent); 3) it is under the control of a small number of, and usually only one, instructors; and 4) while the revision of an entire curriculum is undertaken only after long intervals, the content of a single course evolves more frequently. A course is itself defined in terms of its own "curriculum," or syllabus, and the same four steps of Fig. 1 can be used to design the curriculum of a single course.

This paper is concerned with curriculum design at a single course level, an activity in which every teacher must engage. The scope of this paper is further restricted to the content selection stage (step 3(a) in Fig. 1) in a discipline-based course. The primary purpose of this paper is to present one viewpoint on what are the essential elements of a discipline, and the alternative ways of responding to curricular pressures.

II. ANALYSIS OF COURSE CONTENT

A. Elements of a Discipline

A discipline can be ascribed, and differs from other disciplines in, three basic elements: the *domain*, the *rules*, and the *history*. The *domain* of a discipline refers to the subject matter boundaries of the discipline. The boundaries are only a convenient artifact, erected because the totality of knowledge is too great for comprehension by an individual, and are invariably approximate, tentative, and ever evolving. The *rules*, sometimes also referred to as the fundamentals, concepts, or powerful ideas, are the established ways and tools for knowing

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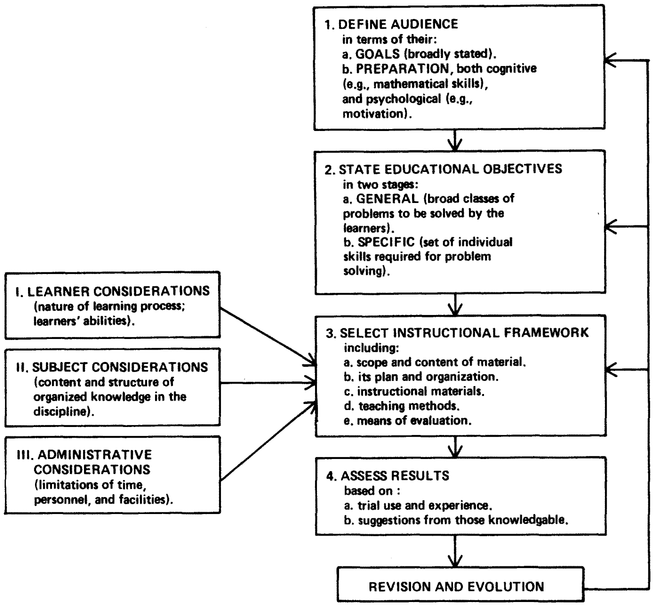

Fig. 1. Outline of steps in the design of a curriculum.

in the domain of that discipline. They consist of demonstrable and describable methods of discovering, generalizing, and validating the knowledge and hypotheses within a discipline. Finally, the *history* of a discipline is the accumulated set of answered (or recognized to be answerable) questions that the discipline has dealt with in the past. A discipline is fully described by these three elements. It follows that instruction in a discipline also requires these elements.

In engineering disciplines, the rules and the history may be liberally translated as "*principles*" and "*problems*," respectively. Each of these two terms, as used here, is to be interpreted broadly. By *principles* we mean two kinds of knowledge. The first may be labeled "axioms," and includes definitions, conventions, reference standards, and symbols; nomenclature, terminology, and classification schemes; units and typical values of parameters; and invariants, like material properties, specifications, and constants. The second may be called "key results," and includes physical laws and mathematical theorems; their corollaries, special cases, and alternative forms; their significance, consequences, and limitations; the established methods and techniques; the empirical rules, formulas, and relationships; and, for engineers, even analogies and solutions to broad, generic, or repeatedly occurring problems. The key results in an academic discipline can have one of two sources. In empirically based disciplines, the key results follow from practice and observation. In theoretically based disciplines, where the models constructed to represent physical objects work well, the key results take the form of a few simple theorems which can be conveniently applied.

Similarly, the term *problems* is used here in a broad sense as case studies in the application of principles, selected from the repertoire of problems which can be solved using the principles involved. It also consists of two parts, namely the formulation of a problem and the solution of a problem. Formulation of the problem includes the assumptions and idealizations, their justification or verification, and the reduction of the problem to a recognizable canonical form. Solution of the problem includes the search and selection of a suitable strategy or alternative, subdivision of the problem into smaller steps, the use of pattern recognition or shortcuts, and an examination of the results for self-consistency or agreement with expectation.

The distinction between principles and problems can be summarized as follows. Principles have a longer lasting and wider range of utility in a broad class of problems. By contrast, problems are more ephemeral, and of a narrow, local interest. Understandably, it is mostly the principles that are common among different courses or books devoted to the same subject. However, the labels "principle" or "problem" are not universally attached to a unit of curricular material; they are only applicable locally within the context of a course. For example, the equivalent circuit of a transistor is a "principle" in a course on transistor circuit design, because it is used for finding the response of a wide variety of circuits. In a course on the physics of semiconductor devices, obtaining the equivalent circuit is a "problem," exemplifying the use of the principles of carrier injection, collection, and transport.

B. Teaching of Domain

The domain of a discipline does not always receive explicit attention during instruction, possibly because teachers believe that it will be learned implicitly, by osmosis, or as a gestalt. In general, the domain of a subject can be described in terms of either its interior or its boundary. The interior of a course is best conveyed by identifying a unifying theme around which the course is structured. The boundary is often harder to delineate because it refers to the hazy periphery and frontiers of the discipline. However, there are sound reasons for teaching both.

Almost all courses have some central theme, usually implied by their titles. Most commonly, the theme is a small set of principles or techniques (example: in a course on electromagnetics, the problems solved may appear to vary a great deal, from electric motors to waveguides, but they all exemplify the use of Maxwell's equations). A particular application can also serve as a theme (example: in a course on solar energy systems, the important principles are many and come from a large number of disciplines, like thermodynamics, semiconductor physics, electrochemistry, heat and mass transfer, and thermal properties of materials, but the common theme is their application to a single problem, viz. obtaining useful energy from solar radiation). In either case, it is desirable that the theme be clear, pervasive, and significant. An unclear focus (or a complete lack of focus) in a course is not only confusing, it prevents seeing the conceptual connections between ideas. The more closely the content is tied to a single theme, the better the momentum, motivation, and attention can be maintained. An extreme example of a weak theme is a book on decibels [4] which covers the subjects of acoustics, noise, instrumentation, transmitters, receivers, television and microwave engineering, and still other topics, connected by the theme that they all express quantities in terms of dB.

The boundaries of a course may be specified by specifying the bounds imposed on the range of validity of principles involved, or on the class of problems or applications of interest. This is desirable both to warn against overgeneralization and to make links with other disciplines. Often, however, a mention of the scope is entirely neglected. For example, it is a rare undergraduate textbook on electromagnetism that points out the limitations of Maxwell's equations by mentioning the need for reinterpretation of field vectors at quantum level and the need for additional terms at very large fields. The purpose of such a mention need only be an awareness of the boundary rather than an understanding of the details of the generalizations.

The domain of a course is best discussed not only at the beginning of the course, but also at the end of the course because its understanding requires a familiarity with the subject matter of the course.

C. Teaching of Principles

Isolation of significant principles from the agglomeration of information is an intellectually demanding activity that all teachers must carry out in their own disciplines. The size of the set of principles is a matter of some concern. Some subjects are rich in specifics and details which are essential, and which cannot be (or have not yet been) replaced by a few general rules distilled from the specifics. As a mastery of copious detail is both difficult and inefficient, the instructor must attempt a clustering on the basis of some common features. Such packaging of details imposes a structure on them and proves helpful because patterns are easier to grasp than amorphous lumps. Learning is still further aided if the packages can be labeled with some (hopefully descriptive) names because of the ease with which words can be mentally processed.

It is clear that the sequential ordering of the individual parts of a course depends only on the principles; the problems normally follow the principles they are intended to exemplify. Often, the internal logic of the ideas determines a unique ordering; for example, in a circuit theory course, Thevenin's theorem must be preceded by the linear superposition theorem, which in turn must be preceded by Kirchhoff's voltage and current laws. Sometimes, the geometrical, hierarchical, temporal, or physical arrangement, rather than logical implication, dictates the order; for example, a radio transmitter may be described by starting at the microphone and proceeding towards the antenna. But there are many circumstances where the order appears to be discretionary. In such cases, an excellent basis for ordering is the richness and motivational value of the problems that can be employed.

D. Teaching of Problems

The problems serve several different but related purposes in a course: 1) illustration (they illustrate the technique or procedure for problem solving), 2) motivation (they show how the more abstract principles relate to real life situations and thus enliven and motivate discussions), 3) drill (they provide practice for reinforcing the already learned problem solving skills), 4) spacing (they act as separators between principles, allowing time for the principles to sink in, demarking the transition from one principle to the next, and accommodating learners with varying learning rates), 5) prototyping (they serve as prototypes and building blocks for the solution of other problems), and 6) scope delineation (they define the domain of utility of a technique of problem solving).

The choice of problems greatly influences the flavor of a course as perceived by the learners, particularly in well-established subjects like electromagnetic field theory, where the individuality of a course is determined almost entirely by the choice of problems. One of the most effective methods of collecting problems of classroom utility is through the professional literature [5]. A gradual substitution of problems dealing with older applications with problems pertaining to newer applications can "modernize" a course. Even a simple change of context, for example, a calculation of B-H power loss due to hysteresis, when transferred from power transformers to computer ferrite-core memory, may help increase student interest and motivation.

It is important that the instructor both solve as well as assign problems to be solved. The solution and assignment of problems serve two distinct purposes, each based in a different principle of learning theory. The inclusion of solved problems is important because imitation is one of the most effective modes of learning. Observing problems being solved is the classroom equivalent of apprenticeship. The assigned problems, on the other hand, require the learners to perform the very task for which they are being prepared. It is well known that a learner learns a task by doing it, and watching the problem being solved is not the same task as solving it.

III. REVISION OF COURSE CONTENT

A. Forces Inducing Curricular Change

Changes in the curriculum of a discipline are caused by a variety of reasons, some internal to the discipline and others external to it. The "internal" reasons are those that can be traced back to block II in Fig. 1, i.e., they stem from changes in the discipline itself; all other changes are "external."

The external reasons for curricular change include such factors as changes in the preparation of entering students; the changing job market for graduates (and hence postgraduation goals of students); feedback from recent graduates concerning the success or utility of the existing curriculum; changes in the availability of instructional materials, personnel, or time; and changes in educational philosophy or interests, either prompted by a change in personnel or simply due to current fads. Finally, changes in the content of one course may influence the curricula of several other related or sequential courses, the so-called "ripple effect."

The internal reasons for curricular change can arise either from changes in the principles of the discipline or from changes in the class of problems of interest. A very striking example of each of these two in electrical engineering curricula occurred during the growth of the semiconductor device field in the 1950's and 1960's. First, the courses in physical electronics were modified to include a new set of principles dealing with transistors, concerning such processes as the depletion, injection, and collection of carriers. These gradually displaced the older principles relating to electron ballistics and electron emission from cathodes, ultimately leading to courses in semiconductor device theory. These courses themselves then shifted to a different and broader set of principles relating to such processes as carrier pair generation and transport theory, which describe not only the transistors but also LED's, solar cells, and microwave devices. Second, the curricula of courses in electronic circuits underwent a change in the class of problems of interest when vacuum tube circuits were replaced by transistor circuits as the vehicles serving to illustrate the same methods of analysis. In addition, the class of problems was enlarged, for example, due to the temperature sensitivity of biasing.

B. Expansion of Knowledge

Of the various factors causing changes in the curriculum, the enlargement of the set of principles in a discipline is undoubtedly the most profound and challenging to the curriculum designer. While the research in the physical sciences creates an ever smaller set of fundamental principles from which all other results can be deduced, the set of engineering principles grows with time because the engineering practice employs an ever widening range of hardware (i.e., physical phenomena, devices, and materials) as well as software (theorems, algorithms, models, etc.). In time, some new knowledge in a discipline may be considered sufficiently basic, or essential to the profession, to merit inclusion in the curriculum of that discipline, thereby creating new demands on facilities, teachers' time, and learners' time. For example, the teachers must invest a sizable fraction of their time to professional renewal so as not to compromise the interest of future students, and this reduces the time available for the current students.

Of interest to a curriculum designer is the demand that the expansion of knowledge creates on the learners' time. On the broader level of the entire engineering curriculum, this is an old problem with few proposed solutions, such as requiring a higher level of preparation for entrance into engineering (presumably from high schools), providing continuing education after graduation, and increasing the number of years required for graduation. At the level of a single subject, an instructor faced with the problem of knowledge expansion has even fewer choices. The duration of a course is usually an invariant due to practical considerations, such as the total length of a program and similar curricular pressures in other courses competing for the learners' time. The rate of presentation of new principles is limited by the comprehension abilities of the learners.[1] When neither of these two options is available, the only alternative is the revision of the curriculum.

C. Responses to the Expansion of Knowledge

A look at the past history of engineering curricula shows that the educators have responded to the expansion of knowledge in several different ways.

1) *Substitution:* The simplest method of incorporating new principles is to replace some of the existing principles with new ones. The main constraint to this method is that only those principles can be dropped which are not required in the subsequent work. As one example of this method in the electrical engineering curriculum, it appears that in the last decade many courses on circuit theory have added new principles, like Tellegen's theorem, and have dropped work with 3-phase circuits, which in turn has become the responsibility of power engineering courses, the principal users of the dropped principles.

2) *Idealization:* As pointed out in Section II-A, the "problem" part of the curriculum consists of "problem formulation" and "problem solution." A favorite method of saving classroom time is to present problems in an already formulated form, stripped of their real-life context, so that they are immediately amenable to solution without going through the exercise of describing the unfamiliar setting or background of the problem and reducing physical or practical situations to a solvable form via assumptions and approximations. This practice is responsible for the often-heard criticisms, for example, that a picture of a working hardware is becoming a rarity in engineering textbooks.

3) *Condensation:* As a next step, new principles can be added to the curriculum by displacing some problems entirely. Usually it is possible to relegate the examples and drill exercises to homework. The net effect is that more principles and fewer illustrative examples or problems of each remain. The process is obviously limited when the problems in the course are one-of-a-kind examples with little overlap and serve only as illustrations rather than as drill. This emphasis on principles is often criticized on the grounds of students having a lack of practice at problem solving, an age-old criticism of academics by many in industry. The criticism has been answered in various ways, for example, by pointing out that the emphasis on principles helps fight obsolescence, that education is only a preface and therefore should be concerned with the principles, and that it is easier to interest a broadly trained scientist in technology than a technologist in broader scientific principles.

4) *Abstraction:* Perhaps the most powerful way of solving the curricular problem due to knowledge expansion is by transferring the principles to a higher level of abstraction. This is done by selecting more general and powerful principles, and treating the older principles as special cases, derived results, or problems. This has the effect of reducing the number of principles. While the principles learned are more powerful, they are also one more step removed from actual applications, thus making the problem solving more involved. This method has also been criticized for decades, indirectly, by saying that engineering education is training "scientists" rather than "engineers." Any number of examples of this method in electrical engineering curricula can be found by comparing typical textbooks in a single field, written about two decades apart. For instance, the various theorems on "tee" and "pi" circuits, discussed in network analysis courses a generation ago [6], are now only examples of the theorems on two-port networks.

5) *Stabilization:* A course that has been reduced to highly abstract, condensed, and essential principles is essentially in a stable state. In electrical engineering, modern courses in some areas, such as electromagnetics, appear to have reached a simi-

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[1] Operationally defined as the sense that an experienced instructor develops for what is an adequate rate in a given situation, such as the rule of thumb that no more than one "major new idea" or two to three "minor new ideas" can be accommodated in a class hour.

lar state. That such a steady-state is reached is to be expected and indeed justified. If the duration of a course is fixed, say at 30 weeks, the course can only attempt to provide the first 30 weeks of learning experience in the field regardless of the present state of the field. And if the field experiences a growth, it just means that after finishing the course a person will take longer to become a practitioner in the field.

6) *Specialization:* Finally, the ultimate response to the expansion of knowledge is narrower specialization. This is indeed how the discipline of electrical engineering was born from the "electrical option" in the curriculum of mechanical engineering early in this century. The birth of the various types of electrical engineering degrees in recent years (e.g., "computer and information engineering" and "instrumentation and control engineering") is a similar attempt at reducing pressures on the curriculum.

In some respects, the above six responses to the expansion of knowledge are increasingly more "drastic" in the order listed. It is natural to expect each to be employed, in that order, only after the previous one has been "used up." Courses in newly introduced subjects often are initially composed entirely of case studies, which are then gradually supplanted by principles as the subject matures and the fundamentals crystallize over the years. One may expect the natural evolution of the curriculum in a field to take place along this sequence of six stages, and many academic offerings can be identified which have indeed gone through these stages sequentially. The maturity of a subject is then indicated by which of the options the educators are presently exercising to deal with knowledge expansion.

IV. AN EXAMPLE

I have taught an introductory course in circuits and electronics for some time in which the curriculum was influenced by the viewpoint presented in this paper. Some of the discussed ideas apply to such a course, and their influence on the course content is briefly pointed out here.

I begin the course on the first day by describing what electronics is in terms of its applications in communication, computation, and instrumentation with which the students may already be familiar. On the last day of the course I come back to the same question, and define electronics in terms of the work done in the course with which the students are now familiar. In addition, I point out the limitations of their models at high frequencies due to the distributed nature of circuit elements (when a wire is no longer a short circuit), at very small sizes due to material inhomogeneity (where a junction transistor is no longer a three-distinct-layer structure), at very small signals due to fluctuations (where a voltage is no longer a steady reading on a voltmeter), and at very large signals due to heating (where charge flow and heat flow are coupled).

In an introductory course there is obviously little opportunity to isolate new principles. I do explicitly point out and label each principle, and make a sharp distinction between it and a problem. The ordering of principles was chosen to enhance the motivational value of the problems. Thus, operational amplifiers were introduced as physical manifestations of controlled sources very early in the course, before capacitors or diodes; as a result, the problems that could be used for illustrating later principles became more interesting and practical than the otherwise dry circuit analysis problems.

Interesting problems for use in the course were found through trade magazines and, although idealized, were stated in their real-life context; thus, a water-level indicator illustrated comparators, an automobile spark plug illustrated transient response, and a fire alarm illustrated the use of diode characteristics. Each solved problem was identified with a specific principle which it was meant to illustrate, and which justified its presence. The number of problems was thus tightly controlled, with more difficult principles illustrated by a larger number of problems, both solved and assigned.

Finally, the possible or proposed changes in course content were examined to classify them under the categories listed in Section III. Thus, the suggestion to drop digital circuits in favor of linear amplifiers was viewed as "specialization," while the proposal to drop hybrid-pi parameters in favor of *h*-parameters was viewed as "abstraction." Such classification helped in making more informed choices.

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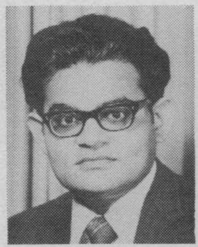

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