Structural Learning and the Design of Educational Materials

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This article is based on two main theses: One, qualitative improvements in education will not come about as a result of rhetoric or superficial proposals for solution made by the so-called "new breed" of educator, but rather as a result of a deeper understanding of the teaching-learning process, and the development and use of new and better principles of educational design. Two, theoretical bases for qualitative improvements in educational design already exist and should be used more widely by educators.

More specifically, this article is subdivided as follows: (1) a brief review of the recent history of educational psychology to provide a perspective for later remarks; (2) a summary of some of the more immediately relevant portions of a new theory of structural learning (Scandura, 1971a, 1973); (3) a discussion of the relationships between basic theory and educational development, particularly as this involves the structural learning theory and related principles of educational design; and (4) some examples of specific educational products developed through the use of some newly devised algorithmic principles of educational design.

Background

For many years, educational psychology and the application of psychology to education were practically synonymous. Courses in educational psychology consisted of frequently watered down versions of principles adapted from the various sub-specialties of academic psychology. Educational psychologists, unfortunately, were able to choose only from among the various competing theories, selecting this one or that, without themselves having anything better to propose.

But times do change. During and after World War II, the urgent need to train personnel to perform complex tasks, and to do so quickly, resulted in the recruitment and involvement of psychologists in designing efficient systems of training. This work continued through the 1950s, and subsequent to increased support for educational research, the movement expanded and was generalized to school learning. Progress during the 1960s was real, and although most of the really complex problems remained unsolved, educational technology began to evolve as a discipline in its own right. It became increasingly clear to all involved that psychology did not have ready-made answers which needed only to be applied.

During this period of the 1960s, "operational objectives," "prerequisites," "hierarchies," "mastery (criterion-referenced) testing" and the like became frequent topics of discussion. Such concepts and techniques have been acclaimed by many educators, and widely used in curriculum construction. They have, on the other hand, been the subject of a good deal of criticism. The most valuable educational objectives cannot be operationalized, some have said. Others point out that the approach leads to fragmented curricula. So goes the story.

It is my contention, based on research on structural learning that is currently underway both in our laboratory and in others, that these criticisms, while they may be partially justifiable, are not inherent in structural approaches to education. We may reasonably expect that present limitations may be overcome in the relatively near future.

Unfortunately, the activism of the late 1960s resulted in a shift of interest from educational technology to the more social and "humanistic" aspects of educational reform. The recommendations made during this period ranged from well-intended (and valid, but rather obvious) warnings that education cannot take place in a social vacuum to high sounding rhetoric and simplistic solutions that have no more scientific validity than alchemy or witchcraft. The torch was passed from serious scientists to so-called experts like Charles Silberman, author of Crisis in the Classroom, and more recently Christopher Jencks with Inequality. These and other authors of the same ilk have dramatically pointed out shortcomings of our schools, something which unfortunately is all too easy, but have suggested nothing solid to take their place.

Largely unnoticed during this period were a number of important developments in such related, yet diverse, fields as formal linguistics, artificial intelligence, Piagetian structuralism, logic and mathematical foundations, information processing psychology, rule learning and some fundamental work in educational design—the confluence of which I have called structural learning (cf. Scandura, 1971b, 1973). Fortunately for the future, the relevance to educational design and curriculum development of recent work in structural learning is being increasingly well-recognized. Prototype educational products, based directly on the theoretical ideas which have evolved, have been developed and tested for effective-

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Preparation of this article was supported in part by NSF grant 6796.

Reprinted from
EDUCATIONAL TECHNOLOGY/August, 1973
ness, sometimes with startling results (cf. Scandura, 1972a, 1972b).

The Theory of Structural Learning

Before reviewing some of these educational prototypes, let us first look at some of the more immediately relevant portions of the theory of structural learning. As those who have followed my research know, over the past decade this research has gone through several phases. My initial efforts, centering about my dissertation work at Syracuse, had the rather optimistic goal of understanding the teaching-learning process in its full complexity. I need not tell the reader that, while some interesting ideas grew out of this work, my initial efforts were something less than a complete success.

The second phase was spent trying to get a better grasp of the problems involved, including the development of suitable research paradigms. This research consisted of a large number of individual studies ranging over a wide variety of phenomena involving complex human learning. A major theme of this research was that rules provide a more appropriate basis for analyzing complex human learning than do associations. Rather than viewing rules as complex networks of associations, it was proposed that associations might better be thought of as special degenerate cases of rules. The full implications of this idea became clear to me only during the last few years.

The fundamental notion of representing knowledge in terms of rules (procedures), together with the introduction of just a few other equally basic assumptions, have provided the basis for a new comprehensive theory of structural learning. This theory consists of three distinct and easily identifiable, but complementary, levels of theorizing, each with its own type of empiricism.

The first level of the theory is concerned with competence—with how to account for the potentially observable behavior of interest to an observer. In this theory, competence consists of a finite set of rules together with laws governing the way in which these rules may interact in accounting for behavior. What is new in the theory is the idea of allowing rules to operate in a higher order fashion, that is, to operate on and to generate new rules. This relatively simple conceptual change not only provides a great increase in explanatory power, but is consistent with how human beings use the knowledge they have. Thus, individuals do not have to be taught explicitly every rule that might be desired. Much of their knowledge is latent in the sense that it can be derived at will when needed from other information which is explicitly available.

The second level of the theory is obtained by adding more structure to the first and deals with the behavior of humans under certain idealized conditions. This idealized theory is concerned with questions of performance, learning, motivation and even perception in situations where the subject is not hampered by memory or his limited capacity for processing information. More particularly, this level of theory does two things. First, it provides a basis for operationally defining the knowledge had by individual subjects. That is, the behavior potential of individuals is determined via a finite testing procedure which essentially "measures" each individual's knowledge relative to the rules in a given competence theory. The idea is not unlike diagnostic testing except that the approach is theoretically more rigorous and empirically more precise (cf. Scandura and Durnin, 1973, Durnin and Scandura, 1973). Second, the theory deals with the question of how and why available knowledge is put to use and how it is acquired in the first place. All learning is viewed as a problem-solving process (Scandura, 1971a). If the subject does not have a rule explicitly available for achieving a given goal, then control is assumed to move automatically to the higher order goal of deriving a rule which will satisfy the original goal. Once such a higher order goal has been satisfied, control is assumed to revert back to the original goal so that the newly derived rule can be applied and the problem solved.

The unrestricted third level of the theory deals also with memory and the limited capacity of subjects to process information. The over-all theory was first outlined in published form in Scandura (1971a) and has been refined and detailed, with a substantial body of empirical research supporting the theory, in a recent book (Scandura, 1973).

Although the main effort to date has been on theory development, substantial beginnings also have been made in developing practical implications of this work for curriculum development and instructional planning, as was suggested above. New approaches to diagnostic testing have been developed together with various kinds of prototype curricula.

During the past four years, an increasing amount of empirical support for the theory has been obtained. Specifically, we have found among other things that: (1) it is both theoretically possible and practicable to determine the knowledge had by individual students, including higher order capabilities; (2) the problem-solving mechanism proposed does provide an adequate basis for explaining problem-solving performance and learning under the idealized conditions tested; (3) the higher order rules method of analysis apparently can be applied to even relatively complex mathematical subject matters, such as geometric constructions with straightedge and compass; and (4) the method is robust—one can "cut corners" and still use the method successfully in broad based curriculum construction.
Relationships Between Educational Science, Technology and Professional “Know-How”

The notion of levels of theory in structural learning is basic to the present view of the relationship between research and development in curriculum development. Also basic to this view is Simon’s (1969) conception of *The Sciences of the Artificial*. Simon begins his monograph by referring to natural science as knowledge about natural objects, and a science of engineering (designing, composing, synthesizing) products of one sort or another which meet certain requirements. In order to synthesize or engineer something, according to Simon, the scientist must have a purpose or goal, and he must synthesize the elements at his command so as to achieve that goal while taking into account the natural laws governing the operation of these elements and the relationships between them.

As an example of what Simon has in mind, consider the task of constructing a curriculum. In particular, consider the task of identifying the content and basic processes (Scandura, 1971b, Chapter One) to be included in an idealized pre-elementary and elementary school mathematics curriculum. In this case, the goal is to come up with a curriculum which is optimal in the sense that it provides maximum transfer potential, given the time limitations, say, of a mathematics program for disadvantaged youth, ages 3 to 12. The task of the curriculum engineer is to devise a systematic way of achieving the goal within the constraints imposed by the theory.

An important point, which is only implicit in what Simon says, is that it is the goal which determines how much of a given theory need be taken into account in the (scientific) engineering of any particular product. This observation provides one reason why the three partial theories proposed above may be useful. They were designed to provide the kind of information needed (or, equivalently, the kind of constraints to be met) in dealing with the various aspects of curriculum construction. For example, in order to identify the content and processes to be included in a curriculum, it is sufficient to consider only those conceptualizations which pertain to competence. Other conceptual information which may be available, such as information dealing with performance and learning, may be ignored for this purpose. In fact, such information would be entirely irrelevant. On the other hand, if one wanted to deal also with the sequencing of knowledge, the assessment of what a subject knows at any given stage of learning and motivation, then other aspects of the theory would also need to be taken into account. In particular, the engineering would be constrained not only by the theory of knowledge, but by the mechanisms presumed to govern learning, performance or motivation, as the case may be. A curriculum which, in addition, deals explicitly and systematically with memory factors would necessarily have to take the corresponding constraints into account as well.

The notion of partial theories (levels of theorizing) is also helpful in another way. It makes explicit the fact that development can never be entirely systematic. Although science can encroach on professional art, there will always be some residual. No matter how adequate a conceptualization is available at any given stage in the advance of science, there will always be certain things that need to be dealt with on intuitive grounds.

The approach using partial theories makes it easier to specify which aspects are being dealt with on conceptual grounds. These aspects can be dealt with systematically (that is, engineered). The aspects which must be dealt with on the basis of professional “know-how” are also identified. Thus, given any conceptualization (for example, a theory of competence), the curriculum constructor may systematically engineer certain aspects of the total curriculum design (for example, its content and processes), and then consciously deal with those aspects of the curriculum for which the conceptualization does not provide an adequate basis (for example, sequencing and motivation). The relationships among Development, Basic Science, Technology and Professional “Know-How” are summarized in Table 1.

Being explicit about such matters could easily result in more efficient large scale development efforts. Furthermore, to the extent that the conceptualizations used adequately reflect that aspect of reality to be engineered, the resulting curricula should not only be better, but they should require relatively less revision than would otherwise be necessary. A certain degree of evaluation and revision, of course, will always be necessary.

**Table 1**

Summary of Relative Contributions to Development and Relationships Between Basic Science, Technology and Professional “Know-How”

**Development**

A goal-oriented process which employs both available technology and professional “know-how.”

**Basic Science.** Theory (conceptualization) provides basic constraints within which a technology must operate.

**Technology.** A goal-oriented process constrained only by available theory. Technology may be defined in terms of a natural theory plus a goal.

**Professional “Know-How.”** The complement of technology relative to development.
Some Specific Educational Products

During the past several years a number of educational products have been developed based directly on the structural learning theory and related technologies. Some of them are only prototypes and all are suggestive only of what might be done given a large scale development effort. Let me review some of them briefly.

Algorithmic Approach to Curriculum Construction. One project was directed toward the problem of building transfer into an actual mathematical curriculum for elementary school teachers. It is impossible to teach students everything one might reasonably want them to know. On the other hand, it had at that time been equally impossible to provide systematically and explicitly for the transfer of what is taught to new situations. The structural learning theory, however, provided an explicit basis potentially for dealing with this problem. In particular, the introduction of higher order rules, according to the theory, would make it possible for subjects to deal effectively with new situations.

In any case, the goal of this project was to construct a curriculum based on explicit rules which the subject would have to learn in order to master the subject—in this case, the curriculum consisted of the mathematics that the elementary school teacher is expected to know in order to do an effective job in the classroom. It was not, however, just a case of identifying a large set of simple rules. Among these rules were included a number of higher order rules by which new rules could be derived. This potential for deriving new rules provided the basis for transfer to new problems. In short, the structural theory of competence provided an explicit basis for constructing the curriculum.

In actually constructing the curriculum we devised the following technology—a technology constrained by the structural theory of competence. First, we went through the chosen text material carefully (Scandura, 1971b), and identified a set of tasks in behavioral terms which reflected the essentials of that material. Second, we identified a set of rules by which each task could be solved. This step goes one beyond the usual behavioral objectives approach in that not only is the information to be learned specified in behavioral terms, but also the procedures (rules) the learner must know in order to generate those behaviors are used explicitly to guide the instruction. In current curriculum development, the curriculum constructor must rely on professional "know-how" as to what ought to be taught and how. The identification of explicit rules puts this on a more systematic basis. The next step, and perhaps the most critical one from the standpoint of the structural theory, was to search for invariants—parallels among the different rules identified. These parallels were typically indicative of the presence of higher order relationships. On this basis, higher order rules were identified; one such rule showed how rules for converting between numerals in arbitrary number bases (e.g., 2, 5) can be derived from a single rule for converting, say, between base 10 and base 8 numerals. Finally, the higher order rules made it possible to eliminate some of the original rules as unnecessary in the sense that they could be derived at will, by application of some higher rule to other lower order rules still left in the curriculum.

In our first go-round through Mathematics: Concrete Behavioral Foundations (Scandura, 1971b), we identified several hundred tasks, and correspondingly, several hundred rules for solving those tasks, one rule for each task. Our higher order rules analysis was limited in the sense that we identified only those higher order rules which were more or less obvious, giving us a total of 12 higher order rules. Instruction in just these 12 higher order rules, however, rather surprisingly made it possible to cut the number of lower order rules to less than half. Our decision to produce the resulting curriculum as a workbook (Scandura, Durnin, Ehrenpreis and Luger, 1971) was, of course, based on pragmatic considerations.

To determine the viability of such a curriculum, Ehrenpreis and Scandura (1972) conducted a study in which the effectiveness of higher order rules was evaluated empirically. In particular, two forms of the rule based curricula were compared. In one treatment, the learners were taught a set of discrete tasks and rules from the original set so that there was one rule for each task. In the other treatment, the learners were presented with the reduced set of rules, including only some of the lower order rules, together with the relevant higher order rules. After training over a fixed period of time, testing indicated that both groups had learned what they had been taught—thereby demonstrating the viability of instruction by rule. What was even more encouraging, however, was that the higher order rules group performed equally as well as the discrete rules group on those tasks on which only the discrete rules group had been trained. Further, the higher order rules group performed significantly better on tasks on which neither group had been trained. In short, the higher order rules group was taught less but learned more.

We have also been engaged in three development projects aimed at specific and critical needs which exist presently in many schools. The first project, the Arithmetical Skills Project, is designed to improve the basic arithmetical skills of addition, subtraction, multiplication and division. Our aim has been to develop efficient methods of self-instruction which would free the teacher to focus on other aspects of elementary mathematics. Our second project, the Critical Reading Project, involves developing a sys-
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Figure 1

Subtraction Algorithm

![Diagram of Subtraction Algorithm]

The specific goals in this project were to identify: (a) the most efficient procedure possible for performing each kind of computation; (b) the best way to sequence instruction on the parts (i.e., the paths) of this procedure; and (c) an efficient method for assessing mastery at each stage.

In order to find efficient procedures which are compatible with the usual computational algorithms, we proceeded as follows. For each arithmetic operation, flowcharts were prepared for the common algorithms which specified precisely what was involved at each step. Programming techniques were then used to combine the alternative algorithms, to eliminate redundancies and to otherwise produce the best possible combined algorithm. This typically involves minimizing the number of paths involved, but such considerations as the difficulty of the paths and prerequisite abilities which could be safely assumed of the pupils also were taken into account. The procedure used for subtraction is represented in Figure 1.

The directed graph at the bottom of the Figure is a form of representation we have developed, which is useful both in pinpointing equivalence classes of tasks for testing and in arranging paths according to difficulty. In fact, all that is necessary in arranging (sequencing) paths according to difficulty is to choose the most direct path (e.g., Path 1) first, then the next most direct paths (e.g., Paths 2 and 3), etc. Notice that the hierarchy is not linear, some paths (e.g., 2 and 3) may not be ordered as to difficulty. The partial ordering imposed in this manner on the above subtraction algorithm may be represented by the following lattice:

![Directed Graph Diagram]

It is this ordering that provided the basis for sequencing the instruction.

Arithmetical Skills Project. The project was based on the conceptual framework provided by the idealized structural learning theory. Essentially, an algorithmic analysis of the basic arithmetical skills was used to identify the procedures underlying these skills. The theory also provides an efficient method for assessing behavior potential—that is, for determining via a finite testing procedure which items in a class of items individual subjects are able to solve and which they are not. In brief, the relevant hypothesis was simply that if a subject has learned a rule (algorithm) or a path thereof for achieving his goal (i.e., solving the task), then he will use it. Further, an extension of the algorithmic analysis provides a means of ordering competencies (i.e., rules, algorithms and paths thereof) according to difficulty. This extension both makes assessment more efficient and provides a basis for sequencing instruction on each arithmetical skill.

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The ordering also provided the basis for sequencing the testing. The assessment procedure (Durnin and Scandura, 1973; Scandura, 1973) involves selecting only single test instances from each equivalence class of tasks (which each path corresponding to a distinct equivalence class). The ordering of paths according to difficulty was used to increase the efficiency further by making it possible to introduce a conditional testing procedure.

Actual development is still underway. Initially, the plan was to use two- or four-track cassette tape recorders, together with student workbooks so as to provide the child with a self-instructional mode where he could work at his own pace. Due to cost factors, this plan has been scrapped for the time being and we are presently working with Harper & Row, School Division, of Evanston, Illinois to produce a series of diagnostic and remedial workbooks on arithmetic computation.

The materials produced at various stages have been evaluated informally with generally positive results. Once they know the basic addition facts, for example, below average students have learned the addition algorithm, using tapes, in a total of about 12 hours' time. Subtraction required about half that time. Subsequent empirical analyses of the selected algorithms themselves showed that they were consistent with children's behavior in the sense that the resulting equivalence classes of items were relatively homogeneous.

**Critical Reading Project.** The primary aim of this project was to develop self-instructional materials for testing and teaching critical reading skills in urban schools. Many children who have learned to read in a technical sense cannot read critically. They can translate written statements into sounds and know what these statements mean, but the ideas come through as fragments, unrelated to a more comprehensive whole.

The Critical Reading Project was based on two conceptualizations. One was a small set of basic semantic inference rules derived from natural deductive systems in symbolic logic. The other was a dimensional taxonomy for classifying paragraphs according to difficulty of detecting the relevance of inference rules. Semantic inference rules parallel their syntactic counterparts in symbolic logic, and operate on meanings. The second conceptualization is essentially a taxonomy for classifying paragraphs according to difficulty of detecting the relevance of inference rules. Difficulty in this case corresponds to the variability of the semantic inference rules required to reason effectively in the various contexts. That is, given any particular syntactic inference rule (e.g., A implies B, A ⊃ B), the generality of the corresponding semantic inference rule needed would depend on the amount of irrelevant information contained in the reading context. The more irrelevant information included, for example, the more general the semantic rule required. In all, five essentially independent dimensions were identified along which reading contexts can vary. These were ordered according to difficulty, or equivalently, the degree of generality required of the underlying semantic inference rule.

Based on these conceptualizations, a useful technique was developed for assessing behavior potential on classes of tasks which vary according to difficulty along a set of independent dimensions, and for sequencing instruction. The technique is described in its original form in Scandura (1968) and is based on experimental results of Scandura and Durnin (1968). A more recent version is described in Lowrey and Scandura (1973).

In the actual development, the most common and important logical inference rules and context dimensions were selected. Reading passages were constructed for each inference rule, at all levels of the dimensions. Some of these passages were used for pretesting to determine the entering level of the students and the others for instruction and posttesting. An inductive method (e.g., learning by example) of instruction was used since it was not yet feasible to attempt a fully algorithmic analysis of the semantic inference rules as was done in the arithmetical skills project.

Our attempts to deal with motivation and other relevant factors were based on professional "know-how." The "stories" were made as varied and interesting as possible, with short, frequent sub-tests included so that each child received just the amount of instruction and practice that he needed. A third grade reading level was used in constructing the stories in order to insure that the difficulties encountered were due to the reasoning required and not reading per se. The complete set of four workbooks, plus tests and instructions for use are being considered for publication.

**Processing Skills Project.** The final project we consider has not been carried out but is included because it could be of considerable value. It is based on the taxonomy of process abilities described in Scandura (1971b). This conceptualization was an attempt to define operationally what it means to "think mathematically," but the skills seem equally relevant in other subject areas. The processes identified were: (1) detecting regularities; (2) the reverse ability of particularizing (constructing examples); (3) interpreting descriptions; (4) the reverse ability of describing ideas; (5) making logical inferences; and (6) the reverse ability of axiomatization.

To implement these ideas in schools, it would be necessary (1) to develop introductory materials which
describes the taxonomy of processing abilities in a variety of subject areas; (2) to provide training for teachers in these skills; and (3) to develop specific curriculum materials which emphasize the use of processing skills.

Evaluation of the project would depend on the answers to such questions as: Can teachers successfully assimilate the taxonomy of processing skills? Do they actually adopt process objectives in their lesson planning and instruction? Does awareness of the existence and nature of general process abilities increase teaching effectiveness? Ultimately, do the students so trained demonstrate increased processing ability (e.g., ability to learn and reason logically)?

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