The Evolution of Instructional Science: Toward a Common Knowledge Base

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What Is (and Isn't) Instructional Science?

Instructional science is a very young discipline that is concerned with understanding and improving the process of instruction. Its major purpose is to prescribe optimal methods to bring about desired learning. It is an applied science that represents a bridge between learning theory and instructional practice, a bridge for which John Dewey (1900) and many others have expressed a great need.

Instructional science is much like the applied science of medicine. That science is concerned with developing optimal methods for curing different types of diseases. In a similar way, instructional science is concerned with developing optimal methods for curing different types of ignorance. Medical science is different from biology, although much of it is derived from biology. Similarly, the science of *instruction* is different from the science of *learning*—it is concerned with what the *teacher* should do (or textbook, or computer-assisted instruction program, or tutor, etc.), rather than with what the *learner* does. Naturally, however, many principles in the science of instruction have been derived from principles in the science of learning.

In addition, the *science* of medicine is different from the *practice* of medicine, although it plays an important role in good medical practice. Similarly, instructional science is different from instructional practice (e.g., instructional development) in that it is concerned with *what* the instruction should be like rather than with *how* to make it that way (i.e., the practices and procedures for actually *doing* or making the instruction). Instructional scientists who are developing the discipline must draw on educational practice (an inductive approach) and a variety of related disciplines (a deductive approach), such as learning theory, cognitive theory, communication theory, and motivation theory.

What Are Some Applications?

Instructional science is concerned with making educational resources, such as computer-based instruction, textbooks, and educational films and TV programs, better at teaching knowledge, skills, and attitudes of all kinds. It is concerned with helping teachers and other instructors and instructional agents to give better class presentations, better CRT responses to user input, better oral responses to student questions, and better explanations to slow students who need individualized help. All of these and many other concerns for the "betterment" of public education entail improving the effectiveness, efficiency, and motivational effects of instruction.

But the need for better methods of instruction does not begin and end with public education. Adult (or continuing) education and distance learning (e.g., "correspondence" schools) need better methods of instruction to prevent attrition. Businesses and the military need better methods to reduce the amount of money and employee time needed for job training. The medical profession needs better methods of instruction for effective patient education and for professional training. Special education needs better methods of instruction to help teachers cope productively with physically and mentally handicapped children. The list goes on and on. All indications are that, as our technological society increases its rate of change, education and training will become increasingly important, and there will be an increasing need to make our methods of instruction more effective, efficient, and motivational.

What Is Needed Now?

In sum, the discipline of instructional science is concerned with improving instruction in all kinds of settings in a direct and immediate way (unlike learning theory, which usually requires considerable creative interpretation and translation to be useful in prescribing methods of instruction). But instructional science is a very young and immature science. It has not yet been developed sufficiently to make the magnitude of contribution that is sorely needed. In fact, the discipline has been characterized by the generation of much *piecemeal knowledge* within decidedly antagonistic camps (especially behaviorist and cognitivist) ever since the pioneering work of Skinner and Bruner (whose intellectual heritage can be traced to Thorndike and Dewey, respectively). George Gropper (1983) has observed in a discussion of the discipline that:

> . . . there is no collegial, or even competitive, building of a common knowledge base with individuals making incremental contributions to it. Instead, there are as many "knowledge

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> bases" as there are contributors. Such profusion, if other sciences serve as a guide, does *not* argue for the maturity or sophistication of the discipline.

There is indeed some truth in all theoretical perspectives. Each theory (or "knowledge base") provides a partial understanding of the real world of instruction in much the same way that each window in an unknown house provides a partial understanding of what the inside of the house is like. Some theories look at the same room through different windows (i.e., from different theoretical perspectives), while others look at completely different rooms (i.e., different types of instructional objectives, such as teaching students how to discover natural laws versus teaching them how to apply the Second Law of Thermodynamics). One of our greatest needs at present is for instructional scientists to recognize that there are *different rooms* in the house and that it is helpful, if not essential, that we look through *more than one window* of each room in order to get a complete picture of what each room is like. Only in this way can we proceed to build a common knowledge base on instruction.

Hence, a top priority for all instructional scientists should be (1) to talk in terms of describing *individual rooms* instead of claiming to be describing the whole house, (2) to clearly identify *which room* is being described, and (3) to use *all windows* in a room so as to arrive at the best possible description of that room. Another of our greatest needs is (4) to attempt to *integrate the descriptions* of the individual rooms into a description of the whole house so that we will know how to use more than one "room" in the same course of instruction.

Instructional science must be able to *prescribe specific methods* for optimizing different kinds of *outcomes* in the same piece of instruction, from such generic skills (or cognitive strategies) as being able to solve problems, being able to discover relationships, and being able to reason logically, to such content-specific skills as being able to recall a certain fact, being able to classify examples of a specific concept, and being able to follow a specific procedure. But it will be helpful in describing each room if we recognize that all rooms have floors of some kind, walls of some kind, doors of some kind, lights of some kind, etc. Similarly, it will be helpful for prescribing specific methods for optimizing each kind of outcome if instructional scientists recognize that achieving each of those kinds of outcomes requires some method components that contribute to optimizing the *effectiveness* of the instruction, others that contribute to optimizing the *efficiency* of the instruction, and still others that contribute to optimizing the *appeal* of the instruction. It is also important to recognize that they all have some method components for *organizing* the instruction, (often called instructional strategies), others for *delivering* the instruction to the learner (e.g., media), and still others for *managing* the learner's interaction with the organizational and delivery aspects of the instruction (Reigeluth and Merrill, 1979).

The purposes of this article are twofold: (1) to encourage individuals in the discipline to think in terms of contributing to a "collegial, or even competitive, building of a *common* knowledge base" by doing the four activities mentioned above, and (2) to briefly describe three recent attempts to do exactly that.

Integrative Models of Instruction

During the past 20 years, substantial knowledge about learning, motivation, and instruction has been developed in the form of principles of instruction; and better instructional strategies have been developed for use in designing instruction. But, as was mentioned above, most of this knowledge has been either too piecemeal or too vague to be very useful to practitioners: teachers, textbook writers, computer software developers, and the like. During the past seven to ten years, three important efforts have been undertaken to integrate a substantial amount of our existing knowledge (and to extend that knowledge where important gaps were found) into *prescriptive models* of instruction. The development of these instructional models (each of which is designed to optimize instruction on a different type of objective or goal) has drawn heavily on such diverse fields as cognitive science (especially information processing theory, artificial intelligence, schema theory, subsumption theory, and the structure of memory), behavioral learning theory, systems theory, communications theory, motivation theory, and educational practice.

There are at least two major types of design considerations: (1) *micro* considerations, which apply to teaching a *single* idea (such as the use of examples and practice); and (2) *macro* considerations, which apply to the teaching of *many* related ideas (such as sequencing and systematic review). About ten years ago, M.D. Merrill and his associates (Merrill and Boutwell, 1973; Merrill and Wood, 1974) began to integrate much of the existing knowledge about micro design considerations (for single ideas) into several models of instruction. Those models, along with prescriptions for their optimal use, are referred to as the *Component Display Theory* (Merrill, 1983).

About six years ago, C.M. Reigeluth and M.D. Merrill and their associates (Reigeluth, Merrill, and

Bunderson, 1978; Reigeluth, Merrill, Wilson, and Spiller, 1978) began to integrate much of the existing knowledge about macro design considerations (for many related ideas) into three models of instruction. Those models, along with prescriptions for their use, are referred to as the *Elaboration Theory of Instruction* (Reigeluth and Stein, 1983). These two sets of models are primarily concerned with strategies to optimize the effectiveness and efficiency of instruction (although the Elaboration Theory also devotes a moderate amount of attention to motivational considerations).

Also about five years ago, J.M. Keller and his associates (Keller, 1979) began to integrate much of the existing knowledge about considerations for the *motivational design of instruction* on both the micro and macro levels. This work led to the identification of four major kinds of motivational requirements that instruction might have: attention, relevance, confidence, and satisfaction (ARCS), and it resulted in the identification of a smorgasbord of motivational strategies from which an instructional developer can pick and choose to meet each of those motivational requirements for any piece of instruction (Keller and Dodge, 1982).

These three sets of instructional models are briefly described below.

What Is the Component Display Theory?

Merrill's Component Display Theory (Merrill, 1983; Merrill, Reigeluth, and Faust, 1979; Merrill, Richards, Schmidt, and Wood, 1977) is a prescriptive theory that was developed to integrate existing knowledge about micro design considerations (i.e., considerations for teaching a single idea). It is comprised of (1) *four models* of instruction, each of which can be used in varying degrees of richness, and (2) a unique *system for prescribing* those models on the basis of the kind of objective for an idea. The degree of richness of each model is then prescribed on the basis of the difficulty of the objective in relation to the ability level of the students.

Each of the four models of instruction integrates knowledge about how to optimize instruction for one of four kinds of objectives for any given idea; and each kind of objective corresponds to a different level of cognitive processing for any given idea. The most fundamental difference is between objectives requiring *recall*, those requiring *application*, and those requiring *discovery*. The other difference is between recall objectives that require *verbatim* recall (or rote learning) and those that require *paraphrased* recall (or meaningful understanding). To summarize, the four kinds of objectives are: (1) remember verbatim, (2) remember paraphrased, (3) apply a generality to "new" instances, and (4) discover a "new" generality. Each of these four kinds of objectives requires different instructional strategies to optimize learning at that level of cognitive processing.

For the most common kind of objective—applying a generality to "new" instances—this theory calls for presenting three major strategy components: (1) a *generality*, such as the statement of a principle or the definition of a concept, (2) *examples* of the application of that generality to specific instances, such as demonstrations of the principle or examples of the concept, and (3) *practice* in applying that generality to new instances, such as solving a new problem or classifying a new example of the concept. The practice should always be followed by informational *feedback* as to whether the student's answer was right or wrong and why. The examples and practice items should be *different* from each other in as many ways as the student is likely to encounter in the real world; and they should be arranged in a *progression of difficulty* from easy to difficult (which may include variation in response mode as well as manipulation of variable attributes). Also, the generality, examples, practice, and feedback should all be clearly *separated and labeled*, as opposed to being in a continuous prose passage, in order to facilitate *learner control*. These strategy components can all be used in live instruction as well as in computer-based or other resource-based instruction.

Learner control (Merrill, 1980) is the Component Display Theory's solution to the problem of individual differences among students and hence is its way of cost-effectively individualizing the instruction. It requires some brief student training in (1) the nature of each strategy component, and (2) the way in which each component helps the student to learn (i.e., to overcome a different kind of learning problem). With such knowledge, the student is well equipped to pick and choose from the "menu" (primarily the generality, the examples, and the practice items) to make his or her optimal instructional design. For example, one student might look at the generality, decide that she knows it, and go straight to one of the most difficult practice items to test herself. On the other hand, another student might feel unsure after looking at the generality and would then study an example, return to the generality to try to make more sense of it, check out another example, and finally start work on the easier practice items. Also, rather than designing "visual" instruction for some students and "verbal" instruction for others, as some instructional scientists have suggested, the Component Display Theory advocates making both representations available to all students, along with some knowledge about how and when to use each, so that students will improve their ability to benefit from both representations. (It is also likely that the vast majority of students are not strictly verbal or strictly visual and can therefore already benefit from having both available if the objective is a difficult one.)

In order to increase the richness of this model, you could increase the number of examples and practice items. You could also enrich each of the three major strategy components (generality, examples, and practice) with such secondary strategy components as (1) an *alternative representation* (e.g., a diagram, picture, or flowchart), and/or (2) an *attention-focusing device* (e.g., underlining, exploded diagrams, or contrasts with common errors). The richest version of this model would include a very large number of examples and practice items, as well as both of the secondary strategy components described above (plus some that have not been mentioned here). But for an easy idea/objective in relation to student ability, the generality alone might be enough.

Space limitations do not allow us to describe the specific nature of, or specifications for, each of these strategy components, nor does it allow us to describe any of the other three models comprising the Component Display Theory. However, an inspection of the publications referenced above will reveal that just this one instructional model from the Component Display Theory incorporates work by Bruner (1960) on alternative representations, especially enactive, iconic, and symbolic; by Evans, Homme, and Glaser (1962) on ruleg (or rule-example) as generalities and examples; by Skinner (1954, 1965) on shaping in the form of progression of difficulty, and on overt responses in the form of practice; by Rothkopf (1976) on mathemagenic information primarily under the rubric of attention-focusing devices and the nature of practice items; by Kulhavy (1977) on feedback for practice; by Horn (1976) on Information Mapping for separating and labeling the strategy components; by Gropper (1974) on stimulus properties and response modes; by Markle and Tiemann (1969), Merrill and Tennyson (1977), and Klausmeier, Ghatala, and Frayer (1974) on strategies for teaching concepts, especially instance divergence (examples and practice items as different as possible from each other) and "matched" or "close-in" nonexamples (instances that demonstrate common errors, specifically overgeneralization in the case of concept learning)—to mention just a few of the most prominent people whose work is integrated into this one model.

An inspection of the publications cited above on Component Display Theory will also reveal the influence of the prose learning people (especially Rothkopf and Frase), the taxonomy people (especially Gagné and Bloom), and the structure of memory people (especially Kintsch and Norman) in the derivation of the four kinds of objectives based on different levels of cognitive processing (including both storage and retrieval). Although the Component Display Theory integrates much existing knowledge, it is also important to point out that some of it was developed independently by Merrill and that a considerable amount of "new" knowledge was developed by Merrill as he encountered gaps in the existing knowledge needed to form such an integrative and complete set of models for different kinds of objectives. The classification of objectives according to both content type and performance level is one example of such original work.

It is very difficult to do justice in such short space to an instructional theory that synthesizes so much knowledge about learning and instruction. For more information, the reader is referred to Merrill (1983), Merrill, Reigeluth, and Faust (1979), and Merrill, Richards, Schmidt, and Wood (1977). The individual strategy components in each model have undergone considerable empirical testing in controlled settings. This body of research has shown significant benefits for all of these strategy components (see Merrill, Olsen, and Coldeway, 1976, for a review). However, no research has been done to test each *whole model* to determine the relative importance and the interactive and duplicative effects of each of the strategy components comprising each of these four models.

The Elaboration Theory of Instruction

The Reigeluth-Merrill Elaboration Theory of Instruction (Reigeluth, 1979; Reigeluth and Stein, 1983) is a prescriptive theory that was developed to integrate existing knowledge about *macro* design considerations (i.e., for many related ideas). It also considerably extends that knowledge where deficiencies were found. It is a major attempt to use both an analysis of the structure of knowledge and an understanding of cognitive processes and learning theories to design strategies for selecting, sequencing, synthesizing, and summarizing the content for a course. It states that, if the instruction is designed according to the appropriate model, then that instruction will result in improved levels of achievement, synthesis, retention, transfer, and motivation.

Most instructional design experts have been using a hierarchical task analysis procedure based on Gagné's (1977) cumulative learning theory. But the hierarchical, learning prerequisite relationship is only one of at least *four major kinds of* *relationships* in cognitive subject matter (one of four major kinds of knowledge structures). And the process of "cumulative learning" is only one of *several major kinds of cognitive learning processes*. Another major kind of cognitive learning process is represented by schema theory (Anderson, Spiro, and Anderson, 1978; Mayer, 1977) and its close cousin, subsumption theory (Ausubel, 1968). The formation of stable cognitive structures through "progressive differentiation" (a form of general-to-detailed sequence for instruction) has been almost totally ignored in current instructional practice, in spite of the monumental pioneering work of Ausubel (1968). The other major kinds of knowledge structures or relationships include conceptual (or taxonomic), procedural (or sequential), and theoretical (or causal) relationships (Reigeluth, Merrill, and Bunderson, 1978).

The elaboration theory integrates both of these major kinds of cognitive learning processes (cumulative and subsumptive) and four major kinds of knowledge structures into *three models* of instruction. It also has a *system for prescribing* those models on the basis of the goals for the whole course of instruction. Goals are classified as to three types, and each type requires the formation of a different type of cognitive structure to optimize achievement of that type of goal. In all three models, an elaborative sequence (a kind of general-to-detailed sequence that is somewhat similar to Ausubel's subsumptive sequence and Bruner's "spiral curriculum") is used to optimize the formation of stable cognitive structures. However, the way the subsumptive sequence is operationalized varies considerably from one type of cognitive structure to another. These operationalizations represent a significant departure from Ausubel's instructional model (while still implementing his learning theory), especially in their attention to information processing theory and to Gagné's hierarchical theory of learning. Unlike the Component Display Theory's models, only one of these three models would usually be used for any given course.

In all three models, the instruction begins with a special kind of overview that (1) chooses one of three dimensions for elaboration in the general-to-detailed sequence (based on the major kinds of knowledge structures) and (2) forms the general-to-detailed sequence by *epitomizing* that knowledge structure rather than summarizing the course content. ("Epitomizing" is defined in the dictionary as "making a part that is representative or typical of the characteristics of the whole." In an instructional context, epitomizing refers specifically to providing *concrete* instances and practice items as well as generalities for a few fundamental and highly representative ideas, whereas "summarizing" means providing only *abstract* generalities for *all* major ideas.) Then the instruction proceeds to add detail or complexity in "layers" across the entire breadth of the content of the course, one layer at a time, until the desired level of detail or complexity is reached. Learning prerequisites are introduced only as they become necessary *within each layer*.

Each model is adjusted in certain ways to make it appropriate for the ability level of the students and the complexity or difficulty of the content. For instance, the amount of material between review-and-synthesis components is adjusted to represent an "optimal learning load," which varies depending on the difficulty level of the content in relation to the ability level of the students. Considerable detail has been worked out on the nature of each model, and even on the procedures for designing instruction according to each model (see Reigeluth and Darwazeh, 1982; Reigeluth and Rodgers, 1980; Sari and Reigeluth, 1982). But research on individual method variables comprising the models is scarce, and no research has been done to test each whole model to determine the relative importance and the interactive and duplicative effects of each strategy component comprising each model. Nonetheless, due to their firm foundation in learning theory, cognitive theory, and the structure of knowledge, and due to their intuitive appeal to educators, there is some call for optimism about their potential for significantly improving the effectiveness and appeal of instruction.

Motivational Design of Instruction

In addition to these two instructional theories, valuable work has been done recently on the motivational design of instruction (i.e., prescriptions for improving the motivational characteristics of any given instruction). This aspect of instructional design has been completely overlooked by most instructional scientists. John Keller (1979) has done some very integrative and highly innovative work in developing a descriptive theory of motivation as it relates to instruction and performance. This work integrates knowledge about motivation from the full range of theoretical traditions, from pure behavioral to pure humanistic.

On the most general level, Keller's theory postulates that motivation is a function of person variables and environment variables. Therefore, it draws on *environmental theories* comprised of conditioning principles and physiologically-based drives (e.g., Hull, 1943; Skinner, 1953), *humanistic theories* that postulate a fundamentally free will as the basis of motivation (e.g., Rogers, 1969), and *social learning theories* that look at the interactions between a person and the environment (e.g., Bandura, 1969; Rotter, 1966). Within the domain of social learning theory, Keller has drawn heavily on expectancy-value theory (e.g., Porter and Lawler, 1968), which proposes that motivation is a multiplicative function of expectancies and values. In addition, Keller has drawn on aspects of attitude theory, decision theory, attribution theory, cognitive evaluation theory, equity theory, cognitive dissonance theory, locus of control, and learned helplessness (see Keller, 1979, pp. 28-30, for references to each of these).

This integrative and innovative work on a descriptive theory of motivation as it relates to instruction has important implications for instructional scientists, but Keller has taken it one step further by developing prescriptions for the motivational design of instruction (Keller, 1983; Keller and Dodge, 1982). The prescriptions include method variables for arousing and sustaining *A*ttention, for connecting instruction to important needs (*R*elevance), for building *C*onfidence in success, and for reinforcing behavior (improving *S*atisfaction). Given the nature of the content and the learners, it is not always necessary to include all four kinds of motivational variables. A special combination of learner/content analysis is performed to identify the motivational requirements of the instruction, and then the specific nature of those requirements provides much of the basis for prescribing which specific method variables to use.

Conclusion

The three efforts summarized above are illustrative of the kind of integrative, multi-perspectived building of a *common* knowledge base that is so sorely needed at this point in the development of instructional science as a discipline. These are early, tentative, and as yet incomplete steps toward a common knowledge base, which will be highly useful to educators, trainers, text writers, computer software designers, and others. There is a need to integrate these micro, macro, and motivational models into a unified prescriptive theory—a set of models—of instruction, as well as to continue to modify and add to each of them. ☐

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RICHARD
An Interactive Computer Program for Rhetorical Invention

John M. Aronis and Sandra Katz

This article describes a computer program written by the authors to automate the tagmemic discovery heuristic (tagmemic matrix).[1] Although the matrix has a history of misunderstanding and misuse, we found that it was a good basis for a computerized questioning technique.[2]

Our program, called RICHARD[3], interacts with a student in natural-sounding language. It asks questions based on the matrix and can respond to the student's input. By applying the questioning technique given by the matrix, it is capable of bringing the student beyond a superficial exploration of his or her subject.

Introduction

In the mid-1960's Joseph Weizenbaum of the Massachusetts Institute of Technology developed a computer program capable of simulating human conversation. The program worked so well that some people refused to believe they were talking with a machine: they insisted that another person was generating the output at their terminal. This program, called ELIZA, was designed to simulate a conversation with a particular type of psychiatrist (Rogerian).[4] ELIZA begins a conversation by asking the question "What is your problem?" When the person answers, ELIZA generates another question based on his or her response. Continuing in this way, the program can carry on an extended conversation. Here is a brief sample. The computer's responses are printed in capitals:

> Men are all alike.
>
> IN WHAT WAY?
>
> They're always bugging us about something or other.
>
> CAN YOU THINK OF A SPECIFIC EXAMPLE?

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