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ABSTRACT

It is now almost universally acknowledged that science education must be rejuvenated to serve the needs of American society. An emerging science of science education based on recent advances in psychological research could make this rejuvenation dramatic. Four aspects of psychological research relevant to science curriculum design are discussed: (1) the state of the reasoner; (2) the mechanisms governing change in reasoning; (3) the delivery of instruction; and (4) the equity of educational outcomes. Taken together, this research suggests that science instruction can and should produce a larger number of citizens and scientists who understand some of the phenomena which contribute to scientific creativity and insight and who know how to add to their scientific knowledge autonomously. Instruction which emphasizes discovery of new ideas, which helps learners gain feedback about their ideas, and which encourages them to assess their own ideas is likely to result in citizens who continue to learn in the future. A 12-page bibliography is appended. Author/LR)

Science Curriculum Design:
Views from a Psychological Framework

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Science Curriculum Design: Views from a Psychological Framework

Abstract

It is now almost universally acknowledged that science education must be rejuvenated to serve the needs of American society. An emerging *science of science education* based on recent advances in psychological research could make this rejuvenation dramatic. Four aspects of psychological research relevant to science curriculum design are discussed: the state of the reasoner, the mechanisms governing change in reasoning, the delivery of instruction and the equity of educational outcomes. Taken together, this research suggests that science instruction can and should produce a larger number of citizens and scientists who understand some of the phenomena which contribute to scientific creativity and insight and who know how to add to their scientific knowledge autonomously. Instruction which emphasizes discovery of new ideas, which helps learners gain feedback about their ideas, and which encourages them to assess their own ideas is likely to result in citizens who continue to learn in the future.

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Marcia C. Linn

THE NEED FOR SCIENCE CURRICULUM REFORM

It is now almost universally acknowledged that science education must be rejuvenated to serve the needs of American society. The National Commission on Excellence in Education (1983), in its well publicized document, concludes that our nation is at risk, stating:

> "We report to the American people that while we can take justifiable pride in what our schools and colleges have historically accomplished and contributed to the United States and the well being of its people, the educational foundations of our society are presently being eroded by a rising tide of mediocrity that threatens our very future as a nation and as a people."

The commission challenges U.S. citizens to work towards educational reform to create what they call a "learning society": a society which is committed to a system of education that allows all members the opportunity to stretch their minds to full capacity to *think* effectively. One essential aspect of meeting this challenge involves reform of science curricula in light of recent advances in psychological research.

The National Science Board (NSB) Commission on Pre-college Education in Mathematics, Science, and Technology in its comprehensive report calls for "sweeping and drastic change" (1983, p. v) to provide the "new basics" in mathematics, science, and technology. The new basics "include communication and higher problem solving skills and scientific and technological literacy -- the *thinking* tools that allow us to understand the technological world around us." (1983, p. v). The NSB commission points out that the new basics are needed by *all* students, and that, to accomplish this objective, new curricula must be developed.

Strong evidence for the need for rejuvenation in science education comes from the results of the National Assessment of Educational Progress (NAEP, 1982). Tests which measure science knowledge have revealed how little information many learners acquire and have drawn attention to individual differences in attainment (NAEP, 1982; de Benedictis, Delucchi, Harris, Linn, & Stage, in press). There has been a steady decline in science achievement scores in the United States. For example, seventeen year olds, as measured by NAEP in 1969, 1973, and 1977, demonstrated seriously diminished science achievement. In addition, large numbers of seventeen year olds do not possess the thinking skills required to draw inferences from written materials or to solve multi-step mathematical problems (NAEP, 1982).

Another reason for rejuvenation of science curricula is that the proliferation of scientific information has changed the nature of the field. Fensham and Kornhauser (1982) report that the first million entries in chemical abstracts took 32 years to accumulate while the second million occurred in the last 2 years. The next generation of science curricula must help learners access, organize, and effectively utilize this vast amount of information. This proliferation of knowledge gives strong motivation to curriculum designers to seek assistance from psychologists and educators who are also addressing issues of knowledge acquisition, knowledge organization, and problem solving

Thus, there has been an absolute decline in student attainment of scientific understanding at the same time as the knowledge to be acquired has increased. To create a society which can provide scientific leadership, make responsible decisions in the voting booth, and offer equitable opportunities for all learners, requires substantial change in how science is taught. Resources available to those responding to this crisis include recent advances in psychological research which suggest how science curricula could be improved. This paper suggests how these advances can be used to rejuvenate science curricula to meet the needs of society.

A SCIENCE OF SCIENCE EDUCATION

This is not the first time nor is it likely to be the last time that observers of science education in America call for reform. Now, however, an emerging *science of science education* based on these recent advances in psychological research could make this reform dramatic. First, knowledge proliferation in science education corresponding to that described for chemistry has characterized our understanding of how students learn. Second, new methodological tools have enabled researchers to address previously inaccessible questions. Before considering the implications of the emerging science of science education for curriculum design, this paper provides an historical perspective on advances in psychological research and discusses the advantages and pitfalls of the new methodological tools. Following this discussion, the remainder of the paper focuses on implications of recent research for curriculum design.

Advances in Psychological Research

Processing Capacity

One area where psychological research offers promise is in identifying parameters of human performance which can be reliably measured and which can explain behavior in a variety of situations. For example, researchers have sought to characterize how much information reasoners can process simultaneously, a factor referred to as processing capacity. Miller (1956) initially identified the magic number seven, plus or minus two, as the number of "chunks" which adults can process simultaneously. Subsequently Mandler (1967) developed a different definition, and identified processing capacity as five. Recently, Simon (1974) has suggested another definition which places special emphasis on the time required to memorize a chunk. All of these investigations reinforce the notion that humans have limited processing capacity. Learners tend to reformulate instructional materials which exceed their processing capacities in ways which may lead to misconceptions or to no learning at all. Thus, important advances in characterizing processing capacity have implications for curriculum reform.

Problem Solving

A second area where the emerging science of science education offers implications is in reconceptualizing what constitute reasoning strategies in problem solving. Reasoning strategies are the processes used to solve scientific problems.

Historically, Piaget described stages of reasoning such as "concrete operations" and "formal operations" to characterize strategies leading to valid inference in problems from all subject matter domains. Formal reasoners can, for example, control variables to achieve casual inference (reasoners use the controlling variables strategy when they design experimental conditions to change only the variable under investigation and keep all others the same). Formal reasoning was seen as the culmination of the development of problem solving ability. Many science education researchers and curriculum developers viewed Piaget's stages of "concrete operational" and "formal operational" thought as characterizing strategies governing scientific reasoning (e.g. Lawson, 1983).

Recently, a change in how problem solving performance is viewed has occurred. Piagetian theory placed major emphasis on valid inference, de-emphasizing the role of subject matter knowledge. Recent research (Linn, 1983) suggests that most rules for valid inference are strongly tied to the subject matter of the problem. New candidates for subject matter independent reasoning strategies called meta-reasoning strategies have received attention and will be described below. A reasonable body of research, also discussed below, suggests that subject matter knowledge strongly influences whether or not reasoners use what Piaget called concrete and formal reasoning.

As has been discussed extensively, there is doubt about the existence of the qualitatively different stages which Inhelder and Piaget (1958) described (e.g. Furby, 1980;

Siegler, 1981). Researchers have found that, although performance on Piagetian tasks correlates with performance on other scientific tasks, successful solution of one Piagetian task appears neither necessary nor sufficient for success on another which seemingly requires the same logical strategy (Linn, 198?). Furthermore, performance on Piagetian tasks correlates highly with measures of general ability (Humphrey & Parsons, 1979; Linn & Swiney, 1981) suggesting that Piagetian tasks measure the gradual acquisition of more powerful reasoning strategies rather than the abrupt change from one strategy to another.

Recent research contributes to a redefinition of what have been historically viewed as problem solving strategies. Piagetian theory, with its emphasis on valid inference, has predominated in the past. Meta-reasoning, defined as the ability to reason about one's own reasoning, now appears to offer greater promise. Recent detailed analysis of scientific problem solving (e.g. Clement, 1982; Greeno, 1978; Larkin, 1981; McDermott, Piternick & Rosenquist 1980; Eylon, 1979), suggests examples of meta-reasoning strategies. Greeno (1976) suggests that a reasoning approach called *strategic planning* is central to scientific problem solving. Strategic planning refers to the ability to consider and combine known information to solve a multi-step problem such as combining axioms and theorems to design a geometry proof. Strategic planning can be seen as meta-reasoning in that reasoners must consider various approaches before selecting a promising one. Another aspect of meta-reasoning is the *testing* of the selected approach to see if it meets the reasoner's needs or if another option should be generated. The method used for testing depends on the subject matter The propensity to engage in testing may be less subject matter specific. Both planning and testing involve the learner in reflection about the solution to a problem. Both can be invoked at the discretion of the problem solver.

Intuitive Conceptions

A third area where psychological research contributes to the emerging science of science education is in how learners construct views of scientific phenomena. Piagetian research drew attention to certain intuitive conceptions but sought to explain them in terms of the previously discussed stages. Current research focuses more on the content of conceptions in each subject matter area than on the similarities across subject matter. In addition, current research reveals that intuitive conceptions tend to be held by adults as well as students, contrary to Piagetian theory. Recent research reveals that reasoners construct views of natural phenomena which they bring to their science classes (e.g. Driver, 1983; Linn, 1983; Resnick, 1983). Reasoners hold conceptions which can be referred to as "intuitive conceptions." These are logically consistent and strongly held conceptions which differ from conceptions held by experts. For example, many seventh through twelfth grade reasoners believe that the weight of a metal object determines how much liquid it displaces and strongly defend this view (Linn & Pulos, 1983a). The view of the world constructed by the reasoner has been extensively researched and has important implications for curriculum design as discussed below (e g. Linn & Siegel, 1983; Stevens, Collins, & Goldin, 1982).

The emerging science of science education, therefore, is characterized by advances in understanding processing capacity, problem solving strategies, and intuitive conceptions. Later sections of this paper discuss the impact of these advances on the *state of the reasoner* (e.g. di Sessa, 1981; Larkin, McDermott, Simon & Simon, 1980; Linn & Pulos, 1983a,b; Sternberg, 1982). the *mechanisms which govern change* in reasoning (e.g. Linn & Siegel, 1983; Linn & Eylon, 1983; Reif & Heller, 1982), the *delivery of instruction* using new technology (e.g. Sleeman & Brown, 1982), and the *equity of educational outcomes* (e g Klein, in press; Linn & Petersen, 1983)

Methodological Issues

The science of science education involves several new methodologies. As new techniques become available, methodological concerns are raised. However, it would be unwise to overshadow the creativity of researchers by criticism of methods. Often valid conclusions can be recognized because they occur in differing methodologies, even when they are only partially supported within each methodology.

The increased concern of researchers with the impact of processing capacity and the role of subject matter knowledge reflects a corresponding increase in methods for characterizing and analyzing such information. Some important issues in employing these methodologies are discussed in this section.

Protocol Analysis

One methodology for investigating the role of subject matter knowledge in problem solving is protocol analysis. Many researchers have respondents think out loud while they solve problems. The researcher then attempts to describe a model of how the reasoner solved the problem by analyzing the resulting protocol. Such an approach has yielded much useful information about problem solving. However, this approach also yields a large amount of data per respondent, thereby necessitating studies with small numbers of subjects. In addition, analysis requires a great deal of experimenter judgement. Because a small number of subjects are used and because experimenter judgement is required to analyze the results, these studies might lack generalizability.

Another possible methodological problem with using thinking-aloud protocols concerns the processing requirements. Some respondents to thinking-aloud experiments appear to be very fluent and may be able to produce their thoughts verbally without employing a great deal of their processing capacity. Other respondents, however, may need to use all of their processing capacity to think and therefore have difficulty incorporating thinking-aloud into their problem solving activities. This problem is especially problematic for young subjects who may have limited processing capacities as well as limited availability of verbal formulas for presenting their thoughts. Thus, in interpreting the results of protocol analyses one needs to consider whether the added requirement that one think aloud might have interfered with problem solving.

The demand features of the thinking aloud environment may also interfere with the validity of the resulting protocol. Presumably the respondent in a thinking aloud situation wishes to appear intelligent to the experimenter. The subject may therefore spend more time planning the solution to the problem and may ask more questions before moving ahead than would be characteristic of this same individual in an autonomous problem solving situation.

Another issue concerns the selection of problems. Problems must be selected not only to demand appropriate reasoning strategies but also to allow analysis of the contribution of subject matter knowledge. Reasoners investigating similar phenomenon often use extremely different problems (e.g. di Sessa, 1981; Clement 1982; McDermott, et. al., 1980). Each group identifies intuitive conceptions: some are at the level of expectations about how objects behave while others reflect models of the physical world. Problems may also differ in their problem solving requirements. Some problems simply do not require planning and, therefore, fail to assess that skill (Dalbey, Tourniaire, & Linn, 1984). Although hardly a new concern in science education research (see Linn, 1977 for a discussion of these issues in a different context), selection of problem features and of response requirements deserves serious attention.

Comparisons of Experts and Novices

A prevalent methodology in current research on problem solving concerns the comparison of experts and novices. Comparison of groups is a common technique for identifying potentially meaningful variables in a new field. This technique has offered insight (e.g. Larkin, McDermott, Simon & Simon, 1980). Nevertheless, results of these studies must be viewed with caution. Experts differ from novices on many factors besides expertise. For example, they usually differ in age and if they differ in age they probably also differ in the character of the learning experiences which they received. When experts and novices are asked to solve the same problems, often one group is solving familiar problems, while the other group is solving unfamiliar problems. Thus, it is important to validate findings from expert-novice studies with other investigations.

Knowledge Representation

An important aspect of current research in psychology relevant to physical science curriculum design concerns how knowledge might be represented. Questions about the representation of knowledge are largely unresolved. Some researchers use computer representations such as production systems, nomological nets, or hierarchical trees. These representations may be chosen because they are ideally suited to the problems but at other times they are chosen because they suit the available technology. Computer models can impose restraints on researchers which stem from the technology rather than from theory as many commentators on artificial intelligence have noted (e.g. Pylyshyn, 1978; Boden, 1977).

The purpose of a knowledge representation clearly influences its form. Production systems, which are weakly structured sets of "if...then" associations, have been popular for developing computer models which perform as expert problem solvers. These models, however, are poor representations of human problem solving. Clancey (1982, 1983a,b), had difficulty converting a production system into an intelligent tutor because although the production system could solve the problems it did not solve them in a manner similar to that used by human problem solvers. Clancey concluded that human problem solvers used loosely structured associations to search their knowledge base, rather than using a production system type organization. Clancey was able to better understand human problem solving by developing a model which characterized the loosely structured associations (Clancey, 1984).

Similar findings are reported in studies of expertise in chess playing. Chase and Simon (1973a, b) and others studying expertise in chess have identified how experts recognize patterns and use those to generate just a few moves. The expert then selects from among this small number of moves by analyzing the consequences of each. This approach is considerably different from an exhaustive search of all the possibilities. Exhaustive search is not efficient even for computers in chess problem solving. However, it turns out to be sufficient for expert performance on many of the problems in the problem solving literature. In spite of the efficiency of this procedure for the computer, since it does not mimic the procedure used by the individual its usefulness for understanding human problem solving and for curriculum design must be carefully evaluated.

Level of Analysis

A large body of recent psychological research relevant to science education operates primarily at the very detailed level of analysis of solutions to individual problems. The detailed level of analysis is reflected in protocol analysis of individuals solving problems and in attempts to model knowledge representations. In contrast, many science education researchers have examined correlational relationships between performance on science problems solving tasks and other attitudes and aptitudes.

The usefulness of combining an information processing approach and a human abilities approach to understanding learning has been discussed by Cronbach (1957; 1975) The human abilities approach has demonstrated that scientific problem solving is strongly related to general ability constructs such as fluid ability and crystallized ability. These findings appear useful in investigating possible aptitude- treatm t-interactions (Snow, 1976; Doyle, 1983). In contrast, they appear to shed little light on the processes which reasoners employ when solving a specific problem (e.g. Linn &

Pulos, 1983 a b; Kyllonen, Woltz, & Lohman, 1982). Thus, it appears that the stable characteristics of individuals which can be measured using standardized tests such as general ability, general anxiety, general attitude towards science, correlate with performance on scientific tasks but do not predict specific performance in learning situations. These stable characteristics may govern the acquisition and use of meta-reasoning strategies, more than the selection of subject matter knowledge for a given problem. Curriculum developers need to know both the specific features of instruction which will foster problem solving and the characteristics of learners likely to profit from it.

In summary, recent advances in psychological research reflect corresponding advances in methodology. The new methods offer promise but also raise some concerns. When interpreting research for curriculum designers, these issues must be considered.

PSYCHOLOGICAL RESEARCH RELATED TO CURRICULUM DESIGN

The emerging science of science education offers useful implications for science curriculum design. Four aspects of psychological research relevant to science curriculum design as mentioned above are discussed in this section: the state of the reasoner, the mechanisms governing change in reasoning, the delivery of instruction and the equity of educational outcomes. This discussion focuses on implications and is not intended as a review of the literature. The research studies described are illustrative of relevant issues rather than representative or exhaustive.

State of the Reasoner

The *state of the reasoner* refers to the knowledge, beliefs, and capabilities of the reasoner. Recent psychological research has been concerned with comparison of reasoners at different states, such as comparisons of experts and novices, to determine which aspects of the reasoner's state change as learning progresses. Characterizing the state of the reasoner at the start of a science class, the observed final state of the reasoner, and the desired final state of the reasoner, will help those designing science curricula.

Two aspects of the state of the reasoner are central to curriculum design. First, the available *problem solving strategies* deserve consideration. Second the view of natural phenomenon constructed by the reasoner in terms of *intuitive conceptions* must be considered. These aspects can characterize the initial state and the desired final states for reasoners.

Problem Solving Strategies

The reasoner's state includes a repertoire of problem/solving strategies. Piagetian theory suggests that strategies for valid inference develop as the reasoner gets older. Valid inference occurs intermittently; even logicians sometimes reason "illogically" in solving abstract problems such as Wason's selection task (Wason & Johnson-Laird, 1972). In contrast, young children often reason validly when assessing fairness of fo 'races and illogically in many other content areas. Much Piagetian-based research, starting with the first replication of Inhelder and Piaget's (1958) studies of adolescents conducted by Lovell (1961) indicates that valid reasoning occurs infrequently and that reasoners correctly use valid reasoning strategies only for certain subject matter and in certain contexts.

Role of processing capacity Several research traditions suggest that the fundamental characteristic of development is the increase in processing capacity rather than an increase in the repertoire of reasoning strategies. A number of theorists (Case, 1974, 1980; Fischer, 1980) have argued that the intermittent employment of logical reasoning stems from processing capacity limitations in the learner. Case (1974) demonstrated that eight and nine year old subjects could employ formal reasoning strategies, which Piaget hypothesized were only acquired during adolescence, if the strategies were taught such that limited processing capacity was required for employing them. Similarly, Scardamalia (1977) demonstrated that increasing the processing capacity demands of controlling variables tasks, by increasing the number of variables to be considered simultaneously, resulted in age related changes in ability to solve the problems. She demonstrated that as children got older they could solve problems with more variables and that the relationship between age and number of variables controlled is strikingly consistent.

Thus, the application of logical strategies may be constrained by available processing capacity. The challenge to the educator (e.g. Case, 1975) is to develop instructional procedures which allow reasoners to solve problems using their available processing capacity. In particular, teachers might supply problem solving strategies which allow logical reasoning with limited processing capacity.

Meta-Reasoning strategies Recent research suggests that meta-reasoning strategies are important components of problem solving (e.g. Sternberg, 1982). Meta-reasoning is the capacity to reason about one's own reasoning. Meta-reasoning includes *planning* the solution to a problem by considering alternatives and *testing* the most promising plan.

To understand reasoner's state of meta-reasoning it has been effective to compare how experts and novices solve problems. As discussed in the methodology section, this approach has both strengths and weaknesses. Recent research focusing on states of reasoning has compared experts and novices to attempt to understand strategies which differentiate these two groups.

Chi, Feltovitch & Glaser, (1980) asked expert and novice physicists to categorize physics problems They found that novices tended to rely on the superficial features of the problems, possibly because they lacked appreciation of what information was relevant for solving the problem while experts tended to categorize problems using the essential information required to generate a solution. The *cues* reasoners use to select problem solutions appear to become more relevant to the solution as expertise increases.

Gains in ability to categorize problems by factors relevant to solution could be viewed as meta-knowledge relevant to "planning." Larkin (1983a,b) argues that experts have planning knowledge not held by novices which facilitates their problem solving. Experts in the Chi, et al. (1981) study appeared to spend a reasonable time in this sort of planning.

Experts appear to develop skill at meta-reasoning or the ability to plan their problem solving approach as the result of experience (e.g. Larkin, McDermott, Simon & Simon, 1980). Much research suggests that this knowledge is tacit. That is, experts have difficulty describing their own planning processes. An interesting question for researchers has been to investigate whether making this knowledge explicit fosters effective planning.

Planning becomes more important as individuals gain expertise because their knowledge increases (e.g. Larkin et al., 1980). In order to access a larger knowledge domain, experts need a procedure for selecting the appropriate information. As discussed above, cueing of solution procedures can be effective or superficial. Gains in planning involve gains in recognizing which features of the problem to consider.

Role of subject matter knowledge and context Logical reasoning occurs infrequently in problem solving possibly because it is inextricably bound to the subject matter and context of the scientific problem (Griggs, 1983; Linn, 1983; Linn & Swiney, 1981). To investigate content effects, Linn and Swiney (1981) studied the bending rods task which was first introduced by Inhelder and Piaget (1958). Linn and Swiney established which variables in the bending rods problem the reasoner considered to be important for the solution. They then asked reasoners to conduct experiments using the bending rods apparatus and demonstrated that reasoners tend to control the variables which they think are important, illustrating the role of subject matter knowledge in problem solving.

Another demonstration of the role of subject matter knowledge comes from Tschirgi (1980). Tschirgi (1980) differentiated "sensible reasoning" from Piagetian logical reasoning. Whereas Linn and Swiney (1981) investigated knowledge about the problem variables, Tschirgi (1980) investigated knowledge and beliefs about the experimental outcome. She asked elementary-age subjects to design experiments to investigate the effects of variables which influence outcomes, such as variables which influence how good a cake tastes. She found that, when designing experiments to determine what variables influence whether or not a cake tastes good, her respondents tended to confound their experiments. They designed experiments such that the resulting cake would definitely taste good. Tschirgi (1980) described this as "sensible reasoning" because the reasoners included in their experimental design the common-sense idea that a cake ought to taste good. These reasoners incorporated their expectations about the reasoning situation into their problem solutions. They expected that they were to achieve "good" outcomes rather than expecting to ~~.~~ally investigate the role of each variable.

The context in which problem solving takes place can also influence reasoning performance. Reasoners may perform differently in a school context than they do in a home context. Linn, de Benedictis, and Delucchi (1982) demonstrated the effect of context on reasoning by comparing a scientific context to a consumer context. Linn et al. (1982) found that reasoners tended to accept claims in advertisements. When Linn et al. (1982) asked reasoners to plan experiments to investigate whether these claims were true, reasoners generally designed relatively unrigorous investigations. Reasoners designed less rigorous investigations for the consumer context than they designed for the scientific context. For example, reasoners controlled fewer variables in the advertising context than they controlled in the scientific context.

These results all point towards the need to include processing capacity, subject matter knowledge, and context in our view of problem solving. It seems reasonable to assume that meta-reasoning can become subject matter and context independent as a result of numerous experiences. Reasoners may initially fail to identify which information is subject matter specific and which is not. By solving many problems in different domains, expert reasoners come to be at least tacitly able to use the subject matter independent procedures effectively in new problems (e.g. Clement, 1982). Curricula can make the subject matter independent features explicit and can also provide diverse examples which illustrate which problem solving procedures generalize from one subject matter to another.

Intuitive Conceptions

It is helpful to expand the conceptualization of the initial state of the reasoner to include the intuitive conceptions of natural phenomena which learners construct. Recent research demonstrates that reasoners hold intuitive conceptions of scientific phenomenon. Intuitive conceptions are consistent ideas, reliably held by the reasoner, which differ from scientific conceptions held by experts. Reasoners appear to construct a view of natural phenomena from personal experience guided by analogical reasoning which is reflected in alternative conceptions about all aspects of science. Interestingly, the alternative conceptions held about a given topic such as electricity generally fall into only a few categories (e.g., Cohen, et. al., in press) and occur consistently in studies of different age respondents (e.g. Driver, 1983; Andersson and Karrquist, 1982).

An example of an intuitive conception occurs in reasoning about displaced volume (see Figure 1). Adolescent respondents asked to predict whether an aluminum cube or a steel cube of equal volume will displace more liquid when submersed, or whether both will displace the same amount, frequently respond that the heaviest cube will displace more liquid (Linn, 1983). Close to 50% of 12 to 16 year olds use an inaccurate rule based on weight for this problem (Linn, & Pulos, 1983a; Pulos, de Benedictis, Linn, Sullivan, & Clement, 1982). When probed, reasoners explain that the weight of an

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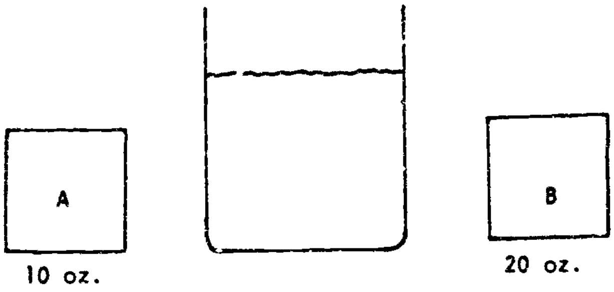
object generally influences experimental outcomes such as how far an object rolling down an inclined plan hits another object. By analogy, they suggest, weight also influences displacement.

FIGURE 1

ITEMS FROM THE PREDICTING DISPLACED VOLUME TASK

1. Blocks A and B are the same size. Block B weighs more than Block A.



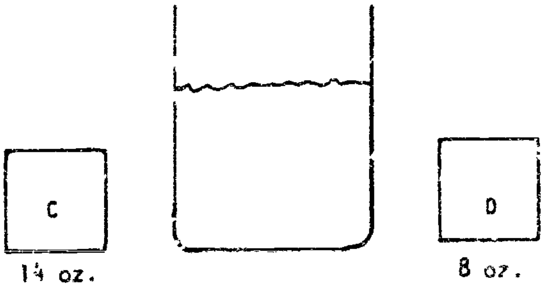
Which block will make the water go up higher?

Block A

Block B

Both the same

6. Blocks C and D are the same size. Block C weighs more than Block D



Which block will make the water go up higher?

Block C

Block D

Both the same

Other commonly observed intuitive conceptions include Aristotelian ideas about mechanics in general (Champagne, Klopfer, & Anderson, 1980; Wilkening, 1981), and about curvilinear motion in particular (McClosky, Caramazza, & Green, 1980; Caramazza, McClosky, & Green, 1981), conceptions of the earth as being round like a pancake (Nussbaum & Novick, 1976), and conceptions of electricity as a liquid (Driver, & Erickson, 1983). Many of these intuitive conceptions are held by a large percentage of the population, including adults. Both Linn and Siegel (1983) and Stevens, Collins and Goldin (1982) provide extensive lists of intuitive conceptions.

The universality of intuitive conceptions both within age cohorts and across the life span is noteworthy. di Sessa (1981) analyzes a series of natural phenomena and notes that the range of intuitive conceptions is small but that the frequency of responses which differ from those held by experts is high. Linn and Pulos (1983b) report that for certain balance beam problems an additive rule is more commonly selected than the correct multiplicative rule. At least in theory, reasoners could choose from among a wide range of intuitive conceptions. In practice, many reasoners appear to construct the same intuitive conceptions.

In the case of predicting displaced volume, for example, the weight of the object is extremely salient. Reasoners use their subject matter knowledge about weight to develop the intuitive conception. They are much less likely to develop conceptions based on the shape of the object such as its height, or the material of the objects such as whether is it metal or plastic. In addition, processing capacity may limit the range of conceptions since reasoners may tend to select conceptions which have only a few variables rather than multiple variables and to consider single variables rather than interacting variables to explain the outcome.

Acquisition of intuitive conceptions Intuitive conceptions characterize the responses of scientists and nonscientists alike to a wide range of scientific problems. All reasoners appear to construct these conceptions. Factors which contribute to this situation include processing capacity limitations, availability of alternatives, and lack of prerequisite knowledge.

Limited processing capacity, as defined above, no doubt contributes to the development of intuitive conceptions in both scientists and non-scientists. When the conceptions of experts are too complicated to fit in the processing capacity of students or of adults who lack prerequisite knowledge, intuitive conceptions may emerge. Reasoners may acquire intuitive conceptions about scientific phenomenon because instruction overloads their processing capacity and they are forced to select a subset of the presented information and use it to solve problems. For example, many have commented that students learn from textbook examples rather than from other information in textbooks.

Eylon, & Helfman (1982) investigated how reasoners use information in the text and in examples when learning physics. They found, congruent with other research (e.g. Mayer & Greeno, 1972), that students failed to learn from text alone, could solve problems similar to the examples they received, and tended to overgeneralize the examples they received to non-isomorphic problems, thereby performing rather poorly on non-isomorphic problems. Thus, respondents relied on the examples and appeared to pay little attention to the text which accompanied the examples. Students might have benefited from instruction which emphasized meta-knowledge about testing isomorphisms between examples and new problems.

In a related study Eylon (1979) demonstrated that instruction in *analogy formation* does help reasoners form conceptions. In her study, physics students received either a) examples, b) text book descriptions of how to solve the problem, c) instruction in how to test the effectiveness of an analogy between one problem and another, or d) a combination of these. Her results suggested that instruction in how to test analogies helped learners form accurate conceptions. These results indicate that learners may benefit from explicit instruction in how to test the isomorphism between the problem and the analogy they choose, as discussed below under mechanisms of change.

Eylon (1979) and Eylon and Helfman (1982) illustrate one way that reasoners form intuitive conceptions. They show that reasoners fail to learn from text and depend instead on the examples. Furthermore, by overgeneralizing examples to new problems, reasoners may gain additional ideas which differ from those held by experts.

These studies illustrate how reasoning progresses. Using analogies, reasoners can construct a view of a natural event with a limited amount of information. Reasoners with limited subject matter knowledge can use an analogical reasoning approach to attempt, and often succeed, in solving problems. The ability of reasoners to employ analogies to solve problems may convince observers that they are using subject matter knowledge which they actually have not acquired.

Analogical reasoning may provide a partial explanation for the low achievement test scores reported by NAEP and others. If reasoners employ analogies widely, as research suggests, then achievement tests which emphasize information as it is presented in the text may fail to measure most of what the learner acquires. These results are consistent with responses of physics instructors to the behavior of their pupils during problem solving sessions: they are universally amazed at how *little* the students know about the subject matter (Larkin, 1981).

Power of intuitive conceptions Intuitive conceptions tend to resist change. Reasoners do not easily abandon their points of view. They are a central part of the reasoner's initial state. For examples, Smith (1980) reports an interview with an 8 year old. The respondent indicated that wood floats and metal sinks. The interviewer asked what the local ferry boats were made of, the respondent said they were made of metal. Then the interviewer asked how the boats could float if they were made of metal. After some thought, the respondent replied "I was wrong, the ferry boats are made of wood." This student denied an accurate recollection to maintain his conception about what floats and what sinks.

Research in the displaced volume task described above reveals a similar response (Linn, 1983). One student, after predicting that the steel cube of the same volume as the aluminum cube would displace more water than the aluminum cube, was dismayed to observe that both displaced the same amount. He quickly accused the experimenter of cheating, saying "You tricked me, you brought magic water."

di Sessa (1981) studying adults' descriptions of what happens when the air intake value of a vacuum cleaner is blocked, reports yet another example of respondents altering their recollections to support their inaccurate conceptions. di Sessa's (1981) respondents often accurately recollected that the motor went faster when the valve was blocked. However, those who used a "work" analogy based on the notion that the vacuum works harder when it has to pick up more dirt sometimes altered their recollection and responded that, after thinking it over, they thought the motor slowed down when the valve was blocked because it was not "working."

Insight from philosophy of science To characterize the state of the reasoner Linn & Siegel (1983) argue that Lakatos' (1972) distinction between the hard core of ideas and the protective belt of ideas might have analogies with the intuitive conceptions which reasoners develop. Lakatos describes the hard core of ideas in a given subject matter domain as those ideas which are unresponsive to data. In the history of science, scientists have persisted in believing the hard core ideas, even when evidence contradicting these ideas was available. In contrast, Lakatos describes the protective belt of ideas as consisting of ideas which are readily changed to defend the hard core.

Reasoners also appear to have ideas which resist change and ideas which are readily modified. In the examples above, reasoners changed ideas which they considered peripheral to their main argument and maintained their hard core of ideas. In the ferry boat example, the reasoner was willing to modify his recollection of what the ferry boat was made out of in order to protect his hard core idea that metal does not float. In the displaced volume task, the reasoner was willing to question the properties of water rather than give up his belief that weight influences displacement. In the vacuum cleaner example, reasoners were willing to modify their recollections of changes in the behavior of the motor in order to support their ideas about "work."

Evidence for the persistence of hard core ideas in intuitive conceptions of scientific phenomenon greatly enhance our understanding of the state of the reasoner. The reasoners' state includes not only the conceptions of scientific phenomenon but also ideas about which aspects of the conceptions are central to the argument and which are peripheral. Reasoners hold on to some ideas which they appear to view as unresponsive to data.

If students have ideas which are unresponsive to data, science educ tors who provide excellent contradictions to students' alternative conceptions are likely to experience frustration. Even contradictions which are seemingly matched to the learners' initial state, may fail to change the students' reasoning. Driver (1983) provides numerous examples of this frustratio . It seems clear that intuitive conceptions characterized by a hard core of ideas are an important aspect c the state of the learner. Curriculum designers must incorporate this understanding into curriculum materials in order to enhance student understanding of scientific phenomenon and also to avoid teacher frustration. Suggestions are offered in the mechanisms of change section, below.

The analogy between Lakatos' philosophy of science and reasoners intuitive conceptions can be pursued further. Lakatos (1972) has stressed that scientific thought progresses even when the hard core of ideas is later shown to be wrong. Lakatos differentiates between a progressing research program and a degenerating research program. According to Lakatos, a progressing research program is one which predicts novel facts. In contrast, a degenerating program fails to predict novel information. He hows that, in the history of science, researc . programs have been followed as long as they predict novel information, even though they also make false predictions.

Linn & Siegel (1983) suggest the value of an analogy between Lakatos' (1972) ideas about groups of scientists and the behavior of individual learners. They propose that individual reasoner's performance in a given content domain can be characterized as following a progressing or a degenerating research program depending on whether the reasoner's ideas can predict novel facts. Reasoners appear to find this criteria adequate as evidenced by the examples above for predicting displaced volume and explaining the operation of a vacuum cleaner. Individuals appear to accept conceptions which account for some of the events in the content domain but not others. The meta-knowledge which reasoners might use to test their ideas and decide whether their conception accounts for *enough* of the events they observe deserves serious attention in science curricula.

Multiple conceptions. Reasoners often hold more than one conception for essentially the same phenomenon. By "the same phenomenon" is meant the actions and interactions of a set of variables. Reasoners seem to select different conceptions for events governed by essentially the same variables.

For example, in the predicting displaced volume problem when experimenters have asked reasoners to predict the amount of sawdust displaced by styrofoam shapes buried in the sawdust, reasoners tend to pay less attention to the weight of the objects and to pay more attention to the space that the objects take up (Sinclair, 1980). Presumably, in this situation, cues about the weight of the objects are less salient than they are when metal cylinders are immersed in water. di Sessa (1981) in the previously mentioned study found that physicists who reason accurately about the concept of work in solving text book physics problems sometimes failed to apply their knowledge of that concept when confronted with his vacuum cleaner problem. Thus, selection of a conception is often *cued* by the subject matter and context of the problem presentation rather than by the events related to the essential variables. Reasoners may construct approaches for solving problems based on superficial features of the situation rather than on the essential elements of the problem. Educators can help students overcome this tendency by emphasizing the essential elements of problems and by presenting numerous examples such that the central features are the only consistencies between problems.

Extensive study of multiple conceptions for a problem with the same essential structure comes from the work of Wason and Johnson-Laird (1972) and Griggs and Cox (1982) on the selection task. In this task the subject matter appears to cue selection of a solution strategy. In the abstract content presentation, the reasoner is confronted with four cards each with an A or B on one side and a 1 or 2 on the other side. The respondent is asked to turn over the card or cards which will test a rule. The rule is: "If there is an 'A' on one side then there is a '2' on the other side." This problem is very difficult, even logicians have trouble with it. In contrast, Griggs and Cox (1982) used more readily understood subject matter. They prepared cards which indicated on one side whether the individual was drinking beer or coke and on the other side whether the individual was aged sixteen or age twenty-two. Respondents were asked to indicate which card or cards they would turn over to test the rule: "If the individual is drinking beer then the individual must be over twenty-one." This problem is considerably easier than the problem with abstract content. The subject matter in the drinking age problem appears to cue selection of an approach based on reciprocity of age and beverage consumed while the abstract condition appears to cue a form of conditional reasoning and to deter reasoners from considering whether there might be an A on the other side of a card with a "1" on it.

Thus, it appears that reasoners hold multiple conceptions for problems with the same underlying logical structure. The subject matter and context of a reasoning problem cues selection of a conception for viewing the problem and ultimately facilitates or inhibits solution of the problem.

Summary

The state of the reasoner as emphasized in Piagetian theory, now requires elaboration. Subject matter knowledge and reasoning context interact with valid reasoning, casting doubt on the centrality of Piagetian reasoning strategies in student performance.

Perhaps the most important aspect of the state of the reasoner for curriculum developers stems from the fact that reasoners generally come to science classes with well developed ideas about natural phenomena referred to as alternative conceptions. These subject matter specific ideas are strongly held and require creative response on the part of science educators as discussed below.

Meta reasoning strategies which are new candidates for subject-matter independent reasoning strategies constitute another important aspect of the state of the reasoner. Developing meta-reasoning skill including planning of problem solutions and testing of the effectiveness of possible solutions offers promise as an objective of science instruction

Mechanisms of Change

Mechanisms which govern changes in conceptions constitute a crucial but as yet largely unexplored area of research. Many have called for investigation of mechanisms of change in reasoning although few have studied these mechanisms. This paper refers to mechanisms of change as procedures or characteristics of the learning environment that lead to changes in the learners conceptions of scientific phenomena.

Perhaps the most important issue in curriculum design concerns mechanisms governing changes in conception. As numerous unsuccessful training studies attest, (e.g. Keating, 1979; Levine & Linn, 1977; Linn, 1980) the mechanisms which govern changes require greater clarification. All researchers considering mechanisms of change agree the an effective mechanism must take into consideration the initial state of the reasoner. As the discussion above illustrated, several aspects of the learners initial state deserve serious consideration. First, any mechanism of change must consider the limitations of the learners' processing capacity. Second, the learner's subject matter specific problem solving strategies determine how the learner incorporates new information. Third, both the availability of math reasoning strategies and the propensity to use them will influence performance. Fourth, the intuitive conceptions the learner brings to science class must be considered. If the learner has a conception for a particular problem then mechanisms of change must address the hard core of ideas and the protective belt of ideas held by the learner. Since many questions about the state of the reasoner remain unanswered, investigations of mechanisms of change are largely speculative.

Historically, mechanisms of conceptual change have received limited attention. For example, Piagetian theory postulates assimilation and accommodation as the mechanisms of change. This theoretical perspective is far too vague to be employed in curriculum design. Another example is reflected in the many textbooks which implicitly assume that reasoning changes will result from the presentation of clearly integrated, logically presented subject matter material. Recent understandings about how reasoners construct views of natural phenomena and tenaciously defend them demonstrate that reasoners do not incorporate new information which is at variance with the conceptions that they hold. In fact, as suggested above, the prevalence of intuitive conceptions which characterize reasoning about much of physical science subject matter knowledge may account for the low performance of students on tests such as the National Assessment of Educational Progress.

Whereas mechanisms of change for intuitive conceptions, especially those that are strongly held, have received limited attention from researchers, such mechanisms have been considered in philosophy of science. Philosophers of science have been concerned with the mechanisms which govern change in the reasoning of groups of scientists working in a particular knowledge domain. Although many of the concerns of philosophers of science focus on procedures used by groups of scientists to understand scientific phenomenon, they raise issues that might also be addressed by researchers considering how to foster conceptual change in individuals or in classroom groups of students.

Elaboration of Subject Matter Knowledge

Frequently reasoners fail to solve problems because they lack relevant subject matter knowledge. An efficient mechanism of change is to elaborate subject matter knowledge as long as the new knowledge does not contradict hard core ideas. Reasoners then use available logical reasoning strategies in conjunction with the new subject matter knowledge to solve the problem. Champagne, Klopfer, & Gunstone (1982) have demonstrated how knowledge elaboration can result in successful physics problem solving. In another example, Linn, Clancey, Dalbey, Heller, and Reese (1983) investigated how reasoners learn to program in PASCAL. They found that reasoners frequently behave as if constructions using DO...UNTIL are equivalent to those using FOR...WHILE. However, reasoners change their ideas quickly when the differences between the two constructions are explained.

Processing capacity. The learners processing capacity places a constraint on the amount of information that can be considered at any one time. Instruction which teaches reasoners how to solve problems using their limited processing capacity has the potential for changing reasoning. Instruction which fails to consider the learners processing capacity and presents conceptions such that learners experie: e information overload, cannot succeed and will tend to be encourage formation of intuitive conceptions.

Knowledge organization To use subject matter knowledge learners must be able to locate relevant information when solving problems. When new knowledge is taught through elaboration it is also possible to elaborate the organization of subject matter knowledge. Many have argued that a hierarchical organization of knowledge can facilitate learning.

An intervention study by Eylon and Reif (in press) illustrates the role of knowledge elaboration and of hierarchical knowledge organization, on physics problem solving. Eylon and Reif (in press) compared performance of college students receiving one of three treatments. The ***hierarchical treatment*** provided knowledge at two levels of detail: An overview followed by detailed elaboration of the overview. The ***single level treatment*** provided only the detailed elaboration of the problems. The ***intensive single level treatment*** provided a double presentation of the single level treatment. They evaluated these treatments using ***local*** tasks which required no reorganization of the information in the detailed elaboration and ***complex*** tasks which required reorganization of the information in the detailed elaboration. All treatment groups performed equally well on local tasks. They found an effect for treatment which interacted with ability on complex tasks. On complex tasks, high ability students in the hierarchical and intensive single level treatment out-performed those in the single level treatment. Medium ability students in the hierarchical treatment out-performed other medium ability students on complex tasks. Independent of treatment, low ability students performed poorly, solving an average of less than 50% of the complex problems correctly. It appears that hierarchical information facilitates performance of medium ability students while high ability students can infer the knowledge they need from information given at a single level. These results are congruent with those of Mayer (1974, 1979) for prose learning and show that the logical organization of knowledge in instruction influences performance.

In a second experiment Eylon and Reif (in press) investigated the effect of two alternative hierarchical organizations of the same physics information. Their results were in the expected direction: Subjects performed better on problems requiring the information emphasized in the hierarchical organization they received. These results are congruent with Shavelson (1973) who showed that reasoner's knowledge structures were the same as those which they encountered in the instructional materials.

Instruction emphasizing knowledge organization appears to influence problem solving because it makes the information relevant to solving a particular problem readily available to the learner. Thus, Eylon and Reif (in press) demonstrated that hierarchical knowledge organizations which are congruent with the problem solving situation result in better problem solving than irrelevant knowledge organizations.

If, as argued above, strategies for valid inference are strongly tied to subject matter knowledge, then instruction emphasizing both might be helpful. Linn, Clement, Pulos and Sullivan (1982) investigated how instruction in problem solving and in subject matter knowledge influenced reasoning performance. The subject matter knowledge training consisted of five class sessions on factors influencing blood pressure, which were adapted from the Health Activities Project (1980). All participants made substantial gains in knowledge about blood pressure. The problem solving training consisted of a 40 minute individual session where participants learned how to set up controlled experiments using familiar variables. The problem solving training culminated in a requirement, met by each participant, to accurately state the controlling variables strategy in their own words. The training was evaluated by asking participants to design and criticize experiments about blood pressure and experiments about bending rods.

The blood pressure subject matter knowledge training fostered performance on problems with blood pressure subject matter. The problem solving training combined with blood pressure subject matter knowledge training further enhanced performance on problems with blood pressure subject matter and also fostered performance on problems with bending rods subject matter.

Analysis of individual responses revealed that the blood pressure subject matter knowledge training increased the number of variables each participant considered while the problem solving training increased the likelihood of participants verbally producing the controlling variables strategy to solve the problems. Furthermore, improved performance on problems with previously unfamiliar variables did not result from problem solving training and only resulted from blood pressure subject matter training. Thus, Linn, Clement, Pulos & Sullivan (1982) show that subject matter and problem solving training have somewhat separate roles in fostering effective performance.

In summary, as long as instruction does not question hard core ideas as defined in the previous section or exceed processing capacity, reasoners' problem solving effectiveness is likely to increase as a result of elaboration of subject matter knowledge. As the studies discussed above suggest, this process is successful because training makes explicit the subject matter knowledge relevant to the problem solution. As the studies above illustrate, subject matter knowledge, knowledge of the hierarchical relationships between subject matter concepts, and valid strategy knowledge can all lead to increased reasoning performance. As these studies also reveal, the determination of which knowledge will be relevant to which type of problem requires careful analysis.

Intuitive Conceptions

As discussed above, contradiction of reasoners' intuitive conceptions generally results in reasoners protecting their hard core of ideas and altering their protective belt of ideas. Mechanisms which govern change in conceptions must respond to this situation.

Progressing research program. One response to contradiction is to modify some ideas while retaining others. Reasoners may protect their hard core of ideas by using their protective belt of ideas. Logical defense of the hard core of ideas has the potential for fostering what might by called a progressing research program. Reasoners following a progressing research program, modify their ideas to account for contradictions and defend their hard core as long as it predicts *some* novel facts. For example, in the case of contradictions to ideas about predicting displaced volume, reasoners may consider variables associated with the size of the object, such as its height, width, circumference, and cross section. Second, reasoners may modify the criteria which govern application of ideas as a result of contradiction. Some reasoners choose not to focus on weight when the weight of the two solids is equal. Linn and Pulos (1983a) demonstrated that many solvers of predicting displaced volume had two categories of response. One category for problems where weight was equal and a second category for problems where weight was unequal. These reasoners have differentiated a single weight-based conception of displacement into two conceptions. Thus, reasoners who protect their hard core of ideas may identify new variables and use them to partition the instances under which their hard core ideas are invoked.

Cueing a new solution. Another response to contradiction is governed by a mechanism called *cueing*. As discussed above, reasoners may entertain several alternative conceptions for problems with the same essential features. The subject matter or other superficial information may cue the reasoner to invoke a certain conception. A change in reasoning could result if the cues which reasoners attend to are changed. The reasoner might then select a different conception. As noted above, Chi, Feltovitch, and Glaser (1980) demonstrated that experts use different cues than novices to solve the same problem. One way to enhance the likelihood of conceptual change would be to influence the cueing process.

Reasoners may identify *new* cues for selecting a solution when they respond to contradictions. When reasoners choose to apply an intuitive conception to 'y some of the instances of a problem such as only cases when weight is unequal, they are changing their ideas. Instruction which encourages learners to alter their protective belts might indirectly increase the importance accorded to a variable which could cue selection of a new solution strategy.

Evidence for cueing of solutions as a mechanism of change comes from a study by Linn, Delucchi & de Benedictis (1984). Students received contradictions to their notions about the role of weight in predicting displaced volume. When students were asked to explain how they came to change their conceptions, many students who changed to a volume rule from a weight rule indicated that they always believed in a volume rule and had not changed their ideas. These respondents may have selected a conception which they had available but which had not been cued previously. These students had the information necessary to form an accurate volume-based rule for predicting displaced volume: They could conserve liquid, they knew that the volume of metal does not change when immersed in water, and they could add volumes together. The many contradictions to their weight rule may have cued an available but less salient conception based on volume.

Cueing can succeed when reasoners have alternative conceptions for the same problem. Thus, part of a cueing-based mechanism of change includes making sure the reasoner has some alternatives. Instruction which increases the pool of conceptions available to the reasoner may facilitate this process. For example, Burbules, Linn, and Nilson (1984) investigated the role of what they called *alternative generation* in fostering conceptual change. Alternative generation consisted of helping reasoners identify the variables and possible hypotheses about predicting displaced volume. After these had been identified reasoners then responded to contradictions about their weight rules for predicting displaced volume. For some respondents, the alternative generation activity facilitated conceptual change. Presumably reasoners are more likely to change their alternative conceptions when they have additional options. In many cases, as in the Linn et. al. (1984) study of predicting displaced volume, where reasoners spontaneously generated a volume rule after numerous contradictions, the alternatives already exist. In other cases however, reasoners may not be aware of alternative conceptions for a particular problem. In these cases instruction which emphasizes alternative generation may be effective.

Meta-Reasoning

Research suggests that expert problem solvers use meta-reasoning skills to solve problems solutions more effectively than novices. This is consistent with the theoretical model of planning put forth by Wilensky (1983) and with writing on planning by Hayes-Roth (1980). A mechanism of change to foster problem solving would be to increase meta-reasoning about selection of problem solutions. Increased meta-reasoning skill might facilitate conceptual change.

Clancey's (1983) research on medical problem solving stresses the centrality of meta-reasoning in problem solving. He postulates that what he describes as "weak associations between observed data and bottom line conclusions" drives problem solving. He suggests that reasoners engage in testing and data acquisition until they are satisfied. The criteria for the termination of testing determines the efficacy of the solution. He argues that a large body of subject matter knowledge is used to test whether the diagnosis is correct, after the diagnosis is hypothesized. Elstein, Shulman, & Sprafka (1978) in their book on medical problem solving lend support to this observation by demonstrating that expert physicians consider only a few diagnoses for a given set of symptoms although many diagnoses could be considered and then test their ideas. Similarly, Chase and Simon (1973a,b) reveal that chess experts have a repertoire of "patterns" of chess moves. Expert chess problem solvers first use these patterns to determine a few alternative moves and they then use their subject matter knowledge to test the alternatives more thoroughly. Thus, good problem solvers appear to have both the ability and the inclination to test initial problem solutions. Testing allows them to discard poor ideas and to pursue good ones.

Good problem solvers have better planning skills. Researchers such as Larkin et. al. (1980) Reif & Heller (1982) and Champagne, Klopfer, and Gunstone (1982) have investigated use of planning in solving mechanics problems. Larkin has modeled the problem solving procedures used by experts and novices. Her model, based on protocol analyses, provides an explicit definition of what she calls planning and suggests that experts engage in more planning than novices. If planning can be explicitly taught, reasoners may spend more time planning and as a result, solve problems more effectively. However, as Dalbey, Tourniaire, & Linn (AERA paper, 1984) report, instruction to foster planning may be resisted by students. In contrast, Clancy, in teaching Pascal, found that requiring planning fostered problem solving.

Further evidence for the role of meta-reasoning in conceptual change comes from Clement (1982) who asked expert scientists to solve physical science problems outside their domain of expertise. These reasoners used meta-reasoning strategies to test their ideas. These experts explicitly described both the ideas which they used to investigate the problems and the mechanisms that they used for testing their ideas. For example, one of Clement's subjects, trying to develop an analogy between the expansion of a spring and the flexibility of a rod talked about the spring as being composed of a series of very short rods. After testing, he abandoned this idea and sought a different one which was based on the amount of material in the spring.

Planning may be related to the cueing process described above. The planning processes which experts appear to use more than novices may include determining which cues should be used for selecting a solution. Novices are far less likely to engage in such planning possibly because they may have fewer candidates for cues. Instruction which increases alternatives and encourages use of the meta-reasoning processes of planning and testing might facilitate conceptual change.

Evolution of ideas. Curriculum materials can help learners by encouraging them to consider more cues before selecting a solution and by helping them generate additional conceptions for a problem. Until learners have experienced a reasonable set of problems they will lack criteria for differentiating relevant from irrelevant cues.

Philosopher of science Toulmin (1972) applied an evolutionary metaphor to the survival of ideas. Toulmin argued that the fittest ideas survive while others eventually become extinct. Evidence suggesting that reasoners entertain multiple conceptions for the same problem is consistent with this view. In addition, refinement of the meta-reasoning strategy of testing could be seen as fostering selection of the most effective cues. Instructional procedures which emphasize the diversity of views held by reasoners and which encourage reasoners to test their views would seem to foster the evolution of better ideas.

Summary

In summary, mechanisms which govern changes in reasoning are available but require better understanding. Mechanisms which *elaborate* subject matter knowledge succeed in extending the subject matter understanding of reasoners as long as they are logically consistent with the reasoners view. These mechanisms fail to change strongly held conceptions. Contradiction, the most widely used mechanism, also generally fails to change strongly held ideas. Instead, a mechanism based on *cueing* of solution strategies, combined with increased meta-reasoning skill, offers promise.

Delivery of Instruction

Delivery of instruction refers to all the characteristics of instructional programs, including the subject matter selected and the methods for presenting the subject matter to students. Historically, there has been controversy between direct instruction and discovery learning with direct instruction referring to the explicit presentation of facts and processes in science and discovery learning referring to the presentation of opportunities for learners to discover important scientific principles by interacting with scientific material.

Delivering instruction which reflects both the initial state of the reasoner and the known mechanisms of conceptual change, will greatly enhance student learning. Identification of initial states and mechanisms of change suggest how instruction should be designed; the mode of delivery of scientific information in science classes requires sensitivity to the response of the learner. Even the best instruction will fail if the learner is uninterested and resists learning.

Direct and Discovery Learning

A main controversy in science education has focused on the advantages of direct or discovery oriented instruction (Welch, 1979). The mechanism of change referred to above as elaboration characterizes direct instruction, and much of the recent textbook material in science education has taken this approach. As previously emphasized, reasoners *can* acquire subject matter knowledge, knowledge about hierarchical relationships among information, and knowledge of valid strategies from elaboration or direct instruction. Reasoners can efficiently incorporate this information into their knowledge structure as long as it is consistent with the conceptions that they hold about the problems being studied, and does not exceed their processing capacity. Direct instruction may not be successful when the information being presented contradicts information held by the reasoner because changing strongly held conceptions requires other instructional procedures.

The direct instruction approach often treats the act of scientific discovery as a unique, unusual, and infrequent event. Students learning science, however, are engaged constantly in the act of discovery, in that they are discovering for themselves principles which were previously discovered by other scientists. Students in a direct instruction format frequently fail to appreciate the analogy between their own acts of discovery in science learning and the acts of discovery in the history of science. They may find science boring and irrelevant. They may see science as an accumulation of information and fail to learn the meta-reasoning skills of planning and testing.

Discovery learning, in contrast to direct instruction, encourages students to figure out scientific principles on their own. Discovery learning is frequently associated with a hands-on approach in which students can conduct experiments in order to identify scientific principles. Understanding of what factors *cue* selections of conceptions for scientific phenomena as discussed in the section on mechanisms of change may result. Students are likely to use and refine testing skills. The most frequent criticism of discovery learning is that it is inherently time consuming. Obviously a student using only discovery learning would complete his or her education prior to reaching any modern scientific understanding. On the other hand, discovery learning is often exciting and can result in students gathering information which they personally find useful. Such learners are likely to feel *responsible* for their learning and motivated to form accurate conceptions.

Although discovery learning is inefficient for imparting large amounts of information, it is potentially the best approach for helping students gain meta-reasoning skills. In discovery learning, students get practice in selecting approaches for problems. They often get feedback showing that their approaches are unsuccessful and they then seek a different approach until they find a solution to the problem. Thus, the students actively practice the skills embodied in planning for a problem solution. They experience generating alternatives, testing them, generating more alternatives, and testing again. They may generate the alternatives essential for conceptual change as emphasized in the section on mechanisms of change. They do this in an independent and autonomous fashion, which is, therefore, likely to be available when solving naturally occurring problems.

Optimal instruction probably includes a balance between direct and discovery learning. Researchers have referred, for example, to *directed discovery* where reasoners are directed to engage in discovery learning in areas which are most likely to encounter experiences which change their alternative conceptions and increase their understanding of scientific discovery Recently Burton and Brown (1982) suggested that new technological tools such as computer tutors might provide more efficient presentation of directed discovery experiences than has been possible in the past. Papert in *Mindstorms* (1980) stressed that computer learning environments such as

LOGO allow reasoners to rapidly develop ideas which would take years to develop in traditional classroom situations. Linn, Fisher, Dalbey, Mandinach, and Beckum (1982) suggested that the precise and interactive nature of the computer learning environment fostered development of planning skill.

In contrast, attempts to replicate these suggestions about LOGO or to implement discovery learning experiences (Leron, 1983; Linn, 1980) suggest that the picture is considerably more complex. Undirected discovery, as numerous educators have documented, infrequently yields the sort of understanding which educators would prefer. Just as in the history of science when large numbers of scientists investigated problems but only a small number of discoveries resulted, in classrooms when a large number of students investigate scientific phenomenon, very frequently a small number of discoveries result.

For example LOGO offers students the opportunity, to discover how to solve problems using a computer. Some users, however, appear to give the computer haphazard instructions and to be pleased when things happen on the screen. These users fail to benefit from the precise feedback available because they do not have precise expectations. These users learn that the software responds but do not learn how to get the computer to solve their own problems. Furthermore, they fail to use the meta-reasoning skill of testing their problem solution and responding to feedback.

The design and impact of directed discovery requires careful thought. Students may avoid discovery and simply enjoy the environment. Although directed discovery can focus students on discovering ideas which the instructor knows are important, these may be discoveries of no interest to the learner. Students who "suffer" through undirected discovery and identify a principle which eluded them at first, sometimes gain insights which do not occur when directed discovery is implemented (Salomon, 1979, Snow, 1976). Furthermore, procedures for directing students to gain the most useful insights are not well established. To better understand this dilemma, this paper considers delivery of instruction in conjunction with the learners' processing capacity, subject matter knowledge, intuitive conceptions, and meta-reasoning.

Processing Capacity

A series of studies emphasize that processing capacity constrains reasoning. Direct instruction can respond to this situation by presenting information that does not exceed the processing capacity of the learner. Case (1975) illustrates procedures for presenting subject matter knowledge and conceptual understanding within the capacity of the learner.

Discovery learning environments may foster construction of intuitive conceptions because limited processing capacity constrains how much information the student considers. Guided discovery learning can address this problem by encouraging learners to consider relevant information and avoid irrelevant information. Intelligent tutoring systems which attempt to model the reasoning processes of the learner (e.g. Sleeman & Brown, 1982) might go further and provide specific contradictions to unproductive intuitive conceptions as well as encouraging consideration of other options for problem solution. Thus, one role for guided discovery is to foster effective use of limited processing capacity

Subject Matter Knowledge

Subject matter knowledge comprises an important element in physical science instruction. Direct instruction is quite successful in imparting subject matter knowledge as long as the knowledge does not contradict intuitive conceptions already held by the learner. Some learners, however, resist this form of instruction.

The question is what and how much to teach. One hypothesis to explain the decline in science achievement tests scores has been that teachers select information to teach and students select information to learn which is relevant to real world problem solving but not necessarily represented on science achievement tests. As scientific knowledge proliferates information selection becomes a bigger and bigger issue. It might be argued that reasoners will benefit more from instruction in procedures for locating information than in acquisition of a large number of facts. Thus in deciding which subject matter knowledge to impart, instructional designers need to consider both the relevance of the information to the learners and the availability of the information in some resource accessible to the learner.

As a number of studies reported above suggest, the organization of subject matter knowledge is critical for later information retrieval (Eylon, 1979; Eylon & Reif, in press). Direct instruction in knowledge organization as reflected in the studies of Eylon and Reif (in press) can be successful. Shavelson (1973a,b) argues that learners acquire knowledge structures which the teacher or text presents. Thus, a component of direct instruction can and should be an explicit emphasis on organization of subject matter knowledge.

One feature which differentiates high and low ability students is the capacity to organize the knowledge presented on their own. A number of studies comparing high and low ability students suggest that high ability students often impose their own organization on knowledge, whereas medium and low ability students demonstrably benefit from having a knowledge organization presented to them. (Doyle, 1983) Thus, to serve medium ability students, instructional delivery should emphasize knowledge organization. On the other hand, high ability students may either not benefit from instruction emphasizing knowledge organization or may have a limited learning experience because the imposed knowledge structure prevents them from developing their own (e.g., Snow, 1976).

Intuitive Conceptions

As discussed above, reasoners construct a view of natural phenomena which they bring to science classes. Intuitive conceptions are an important element of physical science knowledge acquisition which can be featured in instruction. Individual learners construct conceptions before they receive science instruction and can learn to test these conceptions in a discovery environment. Instruction can capitalize on alternative conceptions by asking students to compare their ideas. The learners meta-knowledge about problem solving, may increase as a result of such discussion.

In order to change strongly held intuitive conceptions, direct instruction, even with concrete examples of contradiction, may well fail. The discussion of ferry boats and magic water, above, illustrated that contradiction is not sufficient to change strongly held ideas. Mechanisms of change based on the availability of alternatives and on cueing can be facilitated by guided discovery learning. Effective instruction must offer optimal alternatives for the learner and must encourage students to change the cues used to select problem solutions.

To provide reasoners with alternatives to their own ideas instructors can have students compare their ideas about the same phenomenon. A study of predicting volume by Linn, Delucchi, and de Benedictis (1984) reveals that learning often occurs when two students are asked to resolve differences between their conceptions. Similarly, group instruction methods demonstrated by Nussbaum and Novick (1982) illustrate the advantage of student discussion. When learners are confronted with the ideas of their peers, they frequently engage in negotiations which yield modifications of their own alternative conceptions.

To change cues used to solve problems, guided discovery activities which emphasize new cues are useful. For example, in one study contradictions to predicting displaced volume were not sufficient to change the cues reasoners use, so in transfer items, they reverted back to previous ideas (Linn, Delucchi, & de Benedictis, 1984). In another study, Linn, Clement, Pulos, and Sullivan, (1982), students learned both alternatives and new cues and persisted in using new conceptions.

Meta-reasoning

The ultimate objective in fostering conceptual change is to instill in learners the ability to reason about their reasoning process. This allows reasoners to test their intuitive conceptions and to understand the processes which they use to select conceptions. Direct instruction does not appear to facilitate meta-knowledge about reasoning.

It appears extremely difficult to teach students meta-reasoning skills which they transfer to new knowledge domains. One problem might be that students cannot separate the problem specific information from the content and context independent strategies they are using because those strategies are always closely bound to the subject matter knowledge. Thus, students may have difficulty recognizing meta-reasoning strategies. One approach to fostering meta-knowledge appears to be to provide numerous instructional experiences in a variety of subject matter domains and to continuously point out meta-reasoning strategies. This approach might help students recognize the meta-reasoning strategies which they have acquired.

Discovery learning can potentially encourage development of meta-reasoning skill. Reasoners probably construct intuitive conceptions in informal learning environments which resemble discovery learning settings. Given appropriate meta-reasoning skills, learners could also discover the inadequacy of their conceptions by seeking feedback. Given the tenacity with which learners hold on to their intuitive conceptions, however, unless discovery learning settings are augmented with some instruction in meta-reasoning it may take considerable time before learners recognize that their alternative conceptions fail to predict novel events. If classroom instruction which involves discovery also emphasizes that intuitive conceptions are frequently acquired and that the structure of a particular problem is cueing learners to select solution strategies then they may gain meta-reasoning skill.

Summary

In summary, direct instruction and discovery learning both have a place in the science education curriculum. Discovery learning illustrates the importance of meta-reasoning skill and encourages students to become autonomous learners. In contrast, direct instruction can provide students with the large body of well-integrated scientific knowledge required for those making expert contributions to scientific fields. Combining discovery learning and direct instruction can provide a balance. Overemphasis of either side will lead to incomplete understanding of scientific problem solving and ultimately will detract from the important societal objective of providing scientifically literate as well as scientifically expert individuals.

Equity of Educational Outcomes

Concern with *equity of educational outcomes* has permeated American education and is a tenet of the constitution. As Thomas Jefferson stated "I know no safe depository of the ultimate power of the society but the people themselves; and if we think them not enlightened enough to exercise their control with a wholesome discretion, the remedy is not to take it from them but to inform their discretion." Initially this dictum was interpreted as a mandate for providing the same educational opportunities for all segments of society. With increased educational and psychological research came the realization that equitable outcomes may result when different students receive different forms of instruction (Cronbach & Snow, 1977). This realization has led psychological researchers to investigate the conditions under which different learners are likely to master a particular subject matter area.

Equity of educational outcomes includes consideration of appropriate outcomes for individual learners as well as consideration of appropriate levels of societal attainment. Thus, we are concerned both with the attainments of individuals and with the distribution of those attainments across groups in society. Of particular concern is the distribution of proficiency in science across males and females and across minority groups.

Curriculum design plays an important role in fostering equity of educational outcomes. Psychological research offers some insights into how curriculum designers can have impact on educational equity.

Levels of Achievement

Science knowledge attainment is declining and is distributed unequally. Some variability is useful; other variability is undesired and undesirable. Recently, a dwindling number of individuals have become expert or scientifically literate in physical science. Of special concern has been a decline in achievement among the most able students (Branscomb, 1983; Franz, Aldridge, & Clard, 1983).

Another concern is the distribution of science knowledge. Although differences in science knowledge between males and females and between high and low socioeconomic groups are often documented (Miller, Suchner, and Voelker, 1980) they are not readily explained. Research reports that males have greater expertise than females in science and that those from high socioeconomic groups have greater science achievement than those from low socioeconomic groups (Linn, & Petersen, in press; Stage, Kreinberg, Becker & Eccles, in press). This inequitable distribution of science knowledge has implications for vocational success: The segments of the population which, as a group, achieve less in science are also likely to acquire fewer highly-paid science-related positions.

Both the decline in achievement and the inequitable distribution of knowledge present potential dangers to society. Those who lack scientific literacy may become disenchanted with science and thus not encourage the achievements of others. Worse, individuals may come to fear scientific and technological advances and interfere with the acceptance of new ideas and of new technologies.

Role of experience An important factor contributing to the unequal distribution of science knowledge among pre-college students is unequal *experience* with physical science-based activities. Such experiences seem essential for fostering meta-reasoning strategies Of the potential explanations for inequality, experience is the most readily addressed by educational programs.

A variety of research documents differential experience with science. In general, females have less experience with science than do males (Newcombe, Bandura, & Taylor 1983; Petersen, 1982). In informal settings, females are less likely to visit science centers such as the Lawrence Hall of Science or to have science related hobbies or engage in science related activities with their parents. In school settings, females are less likely than males to participate in advanced mathematics and science courses (Armstrong, 1979). Economically advantaged youngsters are more likely to participate in informal learning experiences in science than are economically disadvantaged youngsters. For example, the economically advantaged are more likely to visit science museums, to have science related activities and books in their homes, and to attend science camps (Estavan, 1983). Similarly, the economically advantaged are more likely to pursue mathematics and science courses at advanced levels (Armstrong, 1979).

As one might expect, experience with science related activities is linked to science achievement. For example, Linn and Pulos (1983a,b) found that courses in mathematics and science had the highest correlation with Piagetian science-related reasoning problems of all the factors they measured (including three aspects of spatial ability, and four aspects of general ability). Although causal relationships between all the varied science experiences and ultimate science achievement have not been well established, the correlational relationship between, for example, courses in science and science achievement is reasonably high.

Role of ability. It has been suggested, but not substantiated, that gender differences in science performance may be mediated by other abilities (e.g. Benbow and Stanley, 1980). Spatial ability is the most commonly mentioned factor, but no mechanism linking spatial ability and scientific reasoning has been established.

Linn and Petersen (1983) conducted a meta-analysis of gender differences in spatial ability. They compared the types of spatial ability which yielded gender differences to the types of science tasks which yielded gender differences. They found that gender differences were observed primarily on forms of spatial ability *not* commonly associated with science achievement. In particular they found some gender differences in the ability to estimate the horizontality or verticality of a rod in a tilted picture frame (the Rod and Frame Test) and in the ability to rapidly rotate a figure through space in a task called mental rotations. On mental rotations very few subjects make errors in selecting the correct alternative although there is reasonable variability in the amount of time taken to select an alternative. In contrast, Linn and Petersen found almost no gender differences on tasks which require analytic ability to combine spatially presented information to solve complex problems (called spatial visualization tasks). Thus gender differences in spatial ability were most common on tasks which required specialized spatial skills and were least common on tasks which required the same sort of analytic abilities common in science problem solving. The speculation that spatial ability might play a role in gender differences in science problem solving is not supported by the distribution of gender differences on spatial ability tasks.

Correlational studies which have used measures of spatial ability to reduce or eliminate gender differences in science performance have met with limited success. For example, Linn and Pulos (1983 a,b) identified gender differences in two aspects of science achievement. They were unable to reduce or eliminate the gender differences in science achievement using measures of spatial ability. They suggested that the high correlations between spatial ability and science achievement for all students may result from a different factor than the factors which contribute to gender differences on each measure.

Role of interest. The teaching of science may create unnecessary *barriers* to participation for some students. In particular, emphasis on mathematics or the "scientific method" may dissuade some students from participating, irrelevant curricula may dissuade others. Science curriculum designers will encourage the participation of as wide a range of students as possible if no artificial barriers are included.

Recently, a number of researchers (e.g. Ridgeway, 1983; Rowe, 1983) have called on curriculum developers to carefully consider mathematics requirements for precollege science instruction. Scientists point out that important science content can be taught without mathematics thus increasing the number of potential students for science courses. If mathematics is not a prerequisite for learning science content then making mathematics a barrier may artificially dissuade students from the study of science. Furthermore, students who study science in courses requiring limited mathematics may come to recognize the importance of mathematics as they proceed and ultimately study mathematics because they need the information to continue their study of science.

Many individuals have come to believe that science is identified with the scientific method of valid inference rather than with important discoveries and creative insights. The emphasis on logical reasoning in science may create an unnecessary barrier to participation in science. To avoid this barrier, curriculum designers are encouraged to capitalize on the nature of scientific discovery. Curricula which point out the analogy between the student's mastery of new material and scientist's mastery of new problems will do a great deal towards broadening the students' view of science.

In summary, differential experience is the most readily addressed explanation for inequality in science achievement, from an educational standpoint. Curriculum designers can, in part, remediate differential experience by providing curricula which encourage all students to participate in science-related experiences. Modification of science curricula such that more students can participate in entry level courses and such that those courses are relevant to learners, would certainly help.

Desired Outcomes

The desired outcomes from pre-college science education are difficult to establish. Much writing on the nature of scientific literacy has occurred (e.g. National Commission on Excellence, 1983; National Science Board, 1983). A policy on equitable science attainment must include consideration of the distribution of knowledge in society, of the needs for public information in a democracy, and of individual needs for satisfaction in vocational and personal activities. Furthermore, implementation of such policies is constrained by our limited understanding of mechanisms governing change in reasoning. All of these concerns occur in conjunction with rapid proliferation of science knowledge and rapid technological advances.

Of particular concern has been the desire to encourage individuals to become expert in science. The National Commission on Excellence in Education has suggested that we greatly increase the number of science courses required in high school and modify the content to better serve society. As the quote from Jefferson above eloquently stated, democracy cannot function without an informed public. The best assurance of intelligent decision making in science policy comes from informing the public so that they have sufficient knowledge to participate in these decisions. Curricula must, however, be relevant to the needs of learners in order for this to occur. Current materials seem unsuited to this task. More instruction using available materials is unlikely to achieve the desired learning society.

Rapid technological advance. Rapid scientific advance is a major factor in the growth and develop of modern nations. Our science curricula need to encourage individuals to participate in this important industry as well as encouraging other members of society to foster these achievements. Science curricula can prepare individuals to cope with rapid change in science knowledge. Only if these changes are welcomed and encouraged can we expect to create a society which takes pride in the scientific accomplishments of its experts and continues to produce such experts. Citizens are repeatedly asked to participate in policy decisions concerning new advances in science such as genetic engineering or computerized recordkeeping. Furthermore, many jobs require employees to change functions with the advent of new technology. Science curricula that prepare individuals to cope with these advances are needed.

Many students complete their last science course at about the ninth grade: their knowledge is likely to be out of date by the time they complete high school. As the popularity of recent magazines such as *Science 83*, *Discover*, and *High Technology* have revealed, individuals in our society recognize that they need to maintain their expertise in science as knowledge advances and as technologies are refined. Our educational programs need to pave the way for this continuing educational activity. Science curricula must not only prepare students to deal with current science information but must also instill in them both the interest and ability to cope with new advances in scientific knowledge.

Individual satisfaction from the study of science often results when individuals can see the advantages of their learning in the solving of real world problems. For example, in health, Cardiopulmonary Resuscitation has been widely taught and has the potential for increasing societal health. In addition, science courses provide information about hazards such as dangerous chemicals and response to hazards such as appropriate antidotes. The relevance of such learning for students is clear and may encourage participation in science courses.

In summary, the preferred scientific accomplishments for reasoners in our society are difficult to characterize but some important considerations can be identified. First, science curricula can alert students to the wide range of options available for gathering scientific information such as periodicals, science centers, and computerized data bases. Second, since our society is experiencing rapid change in scientific knowledge and frequent breakthroughs in physical science understanding it is important to prepare individuals to solve new real world problems as they arise. Third, to foster personal satisfaction and societal well-being, science instruction can provide information in areas such as health and safety, which are relevant to the individual. Fourth, instruction which introduces new technologies and new advances can emphasize the job opportunities in these areas and thus encourage participation in science-related vocations.

Procedures for Achieving Equity

Perhaps the single most effective way to foster equitable outcomes from science instruction is to encourage effective instruction. All learners profit from good teaching. Those who have difficulty may profit only from good instruction. Others may learn in spite of mediocre instruction.

Different forms of instruction may be required to bring different learners to the same level of achievement. In particular, individuals who lack experience in science may need instruction which provides that experience. Learners with high general ability may require discovery learning while those of low general ability may require a great deal of explicitness in instruction. Research on aptitude-treatment-interaction is central to equity of educational outcomes (Cronbach and Snow, 1977).

For example, a dilemma in using elaboration as a mechanism of change to achieve equity of outcomes concerns the role of explicitness. Explicit instruction concerning how to solve a scientific problem often results in excellent problem solving but may not generalize to other related problems and may not be recalled if the problem is encountered at a later time. Especially for high ability learners, explicit instruction may be counter-productive. As Doyle (1983) reveals in a comprehensive review, high ability learners are likely to learn more and to retain it for a longer period of time if they are required to discover the solution to problems on their own. In contrast, some students may not be able to discover these solutions on their own and are likely to profit from explicit instruction in how to solve the problems. Curriculum designers using formative evaluation activities might find it particularly useful to pay attention to the role of explicitness as it interacts with general ability.

Reasoners who hold intuitive conceptions about an area require different forms of instruction from those who hold incomplete conceptions. Great inequities can result if elaboration is used for all learners when some of those learners hold intuitive conceptions and therefore, fail to benefit from elaboration. In order for instruction to achieve equity of educational outcomes, careful diagnosis of the initial state of the learner is essential and instruction which matches the learner's initial state is needed.

Summary

In summary, science curriculum design can play a role in the achievement of equity in science learning. Curricula which take into consideration the existing achievements of reasoners have greater potential for bringing all reasoners to appropriate achievement at the end of their schooling. Excellent instruction will serve all learners.

To achieve equity of educational outcomes, it is especially important to insure that students do *not* avoid the study of science because of artificial barriers. Barriers such as advanced mathematics requirements or emphasis on the "scientific method" which are not central to expertise in science should be carefully reviewed. Pre-college science curricula have, as a primary purpose, the presentation of scientific information that will serve reasoners throughout the life span. In addition, they have the purpose of enticing students to study science. If these courses succeed, they will greatly enhance societal scientific literacy.

Science curricula which prepare students to deal with advances in science throughout their life span need to emphasize meta reasoning skills. These skills will enable students to become autonomous learners. One vehicle for insuring that reasoners continue to incorporate new advances in science into their reasoning is the public science center. These centers and other sources of science information can help to remediate intuitive conceptions about new advances in scientific phenomena and, ultimately, can create a citizenry educated to intelligently deal with science policy issues.

CONCLUSIONS AND IMPLICATIONS

The "rising tide of mediocrity" described in the recent report of the National Commission on Excellence in Education (1983) must be reversed. To substitute excellence for mediocrity a change in both the quality and the quantity of instruction is required. Our nation's schools can create a learning society and can teach the "new basics." Such a change requires a concerted and thoughtful effort at curriculum reform. The emerging science of science education can have a lasting impact on science curriculum design provided that recent research findings are considered by those developing the curricula.

Schooling is a complicated inter-dependent combination of forces. To achieve lasting change in education, it it necessary to influence the curriculum, the teachers, the students, the administration, the community, and the political decision makers who set policy and provide school funding. Here we focus specifically on curriculum design. In order for modifications of curriculum programs to have an impact on students, however, all aspects of schooling must be considered.

Qualitative Change in Science Curriculum

Recent psychological research suggests that qualitative changes in science curricula will be effective. Science instruction can encourage students to be autonomous learners. In particular, it is suggested that emphasis on discovery learning in the design of curriculum, will produce a larger number of citizens and scientists who appreciate acts of discovery and who understand some of the phenomena which contribute to scientific creativity and insight

Discovery plays an important role in scientific problem solving and is especially relevant to the solution of everyday scientific problems which learners are likely to encounter after they have completed their last science course. Individuals who have the capability of intelligently employing meta-reasoning strategies to solve naturally occurring real world problems, will meet the demands of the National Commission on Excellence for a learning society.

For example, to achieve a learning society, instruction can emphasize that contradiction is not sufficient to change the conceptions held by individuals. Reasoners who are themselves aware that contradictions will not necessarily change their intuitive conceptions are better able to learn from new experiences.

Autonomous learners can gain additional information after they have completed their last science courses. Instruction which emphasizes discovery of new ideas, which helps learners gain feedback about their ideas, and which encourages them to assess their own conceptions is likely to result in citizens who continue to learn in the future.

Quantity of Science Instruction

As the above discussion of psychological research aptly illustrates, reasoners come to science classes with conceptions about natural phenomenon which are relatively resistant to change. Without intensive and innovative educational efforts, these intuitive conceptions are likely to persist into adulthood. It is clear that changing conceptions held by individuals requires a reasonable amount of instructional time. In the past, science education has not received sufficient time to reliably modify the intuitive conceptions held by learners. Change in the quantity of science instruction seems appropriate in light of the proliferation of science knowledge and in light of our increased understanding of how reasoners change their conceptions.

Mathematics instruction not only takes up a great portion of pre-college instruction but also involves a reasonable amount of repetition of the major concepts involved. Students, for example, are introduced to division first with whole numbers without remainders, then with whole numbers with remainders, then with fractions, etc. Thus, the main concept of division is presented many times in the curriculum. Students who initially have intuitive conceptions about division ultimately overcome those misconceptions. In contrast to mathematics, science instruction frequently lacks repetitiveness. Science courses often introduce a concept and assume that students have acquired it without either checking to see if that is the case or offering an extension of the concept in a new domain in subsequent instruction. It would seem useful to intensify the science curriculum in order to emphasize a small number of conceptions and to present those conceptions in a variety of domains. In this way, intuitive conceptions might eventually be replaced by conceptions held by expert scientists.

Thus, both the quality and quantity of science instruction needs to be modified in order to respond to the crisis in science education. Qualitatively, science instruction could incorporate a stronger emphasis on the problem solving processes which characterize scientific discovery. Quantitatively, science instruction could increase the intensity and frequency with which science concepts are presented in the curriculum

Implementation of New Curricula

Advances in psychological research reveal ideas which generally resonate with the knowledge of expert science teachers. The most reflective teachers will have expertise which reflects an understanding of the findings of recent psychological research and attracts them to curricula based on these findings.

As recent psychological research reveals, expertise is not always accompanied by explicit understanding of the procedures which are used to display that expertise. Many expert teachers may be unaware of the procedures that they use to achieve educational outcomes. They may have tacit knowledge of their expertise which has not been made explicit. An important approach for incorporating the findings of recent psychological research into the practice of teachers is to encourage expert teachers to make their expertise explicit and then to relate the explicit reports of those expert teachers to psychological investigations relevant to their teachings. Some successful professional development programs such as the Bay Area Writing Project (Gray and Mayers, 1978) employ this approach.

Teachers who have conceptions about educational practice which differ from those of expert teachers are likely to hold them tenaciously just as students hold intuitive conceptions of scientific phenomena. The same notions which apply to changing students conceptions of scientific phenomenon can also be applied to changing teachers ideas about instruction. It is useful to identify the intuitive conceptions that teachers have, it is important to recognize that contradiction may be an inappropriate vehicle for changing those conceptions and that meta-reasoning skills will allow teachers to autonomously regulate their own learning. Finally, professional development programs which provide numerous opportunities for consideration of alternative instructional approaches are most likely to succeed.

Response to the Crisis

Response to the crisis in science education requires a concerted, thoughtful, and innovative approach. The participation of curriculum developers, of teachers, of school administrators, of students, and of parents is essential for the success of this endeavor. The emerging science of science education provides some interesting opportunities for fostering both qualitative and quantitative change in science instruction. Certainly quantitative change without qualitative change is unlikely to achieve the objectives which all the various commissions have described as essential.

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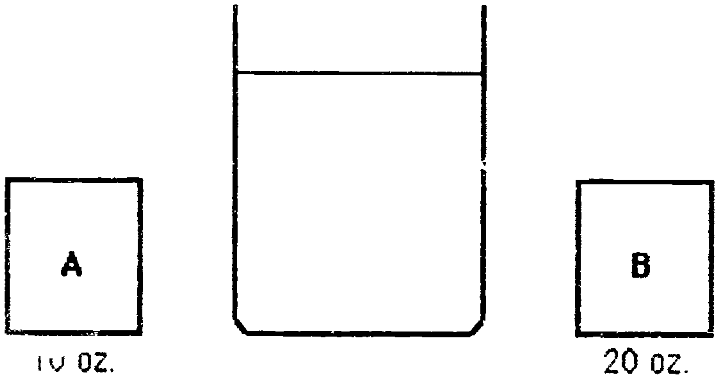
1. Blocks *A* and *B* are the same size Block *B* weighs more than Block *A*



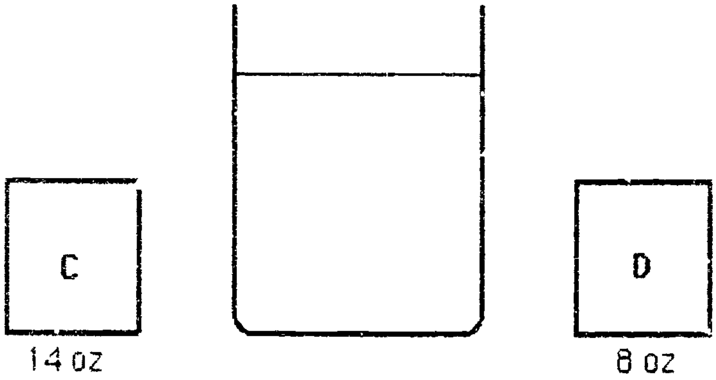
Which block will make the water go up higher?

Block *A*

Block *B*

Both the same

2. Block *C* and *D* are the same size. Block *C* weighs more than Block *D*.



Which block will make the water go up higher?

Block *C*

Block *D*

Both the same