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ABSTRACT

Suggested in this paper are priorities for the role of cognitive psychology in science/mathematics curriculum development and teacher education. Areas discussed include: (1) science education as a national concern; (2) how rapid advances in science knowledge and cognitive psychological knowledge have created a sense of urgency about developing a modern "science of science education"; and (3) the impact of cognitive psychology on science and mathematics education. Considered in the latter area are: a framework for a science of science education, advances in cognitive psychology important for a science of science education, findings from cognitive psychology of interest to curriculum developers and teacher educators (including the development of alternative conceptions), and likely concerns of cognitive psychology, such as research on the organization of the mind, which may have a profound impact on the science of science education. (JN)

Presentation to National Commission on Excellence in Education

The Importance of Cognitive Psychology in Curriculum Development and Teacher Education

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In calling for continued Federal support for cognitive psychological research which impacts on science and mathematics education I draw on twelve years of experience evaluating science and mathematics education programs and conducting cognitive psychological research specifically designed to aid teacher educators and curriculum developers. In order to maintain our excellence in science and mathematics education, we must maintain the impact of cognitive psychological research on curriculum development and teacher education. This paper suggests priorities for the role of cognitive psychology in curriculum development and teacher education in 1982.

We need an empirically based, rapidly developing science of science education, informed by cognitive psychology to ensure our leadership in this field. Developments in cognitive psychology which have influenced the current science of science education and which could potentially revolutionize a future science of science education are delineated. Before describing a science of science education, however, I discuss why science education is a national concern and how the rapid advance in science knowledge and cognitive psychological knowledge create a sense of urgency about developing a modern science of science education.

SCIENCE EDUCATION IS A NATIONAL CONCERN

The strength of the United States lies in its technology. A major component of our national defense is our advantage in the area of technology. Excellence in science education ensures that we can continue to maintain our technological advantage. Our advantage in science education stems, in part, from cognitive psychological research.

Evidence for the value of American technology comes from recent crimes. Alleged thefts of microchips from companies in Silicon Valley, reportedly engineered by the Soviet Union, attest to the value of American technology. Our technology is sufficiently important to foreign governments, that they appear to engage in crime to acquire it (San Francisco Cronicle, March, 1982).

This conclusion stems from examination of high technology surveillance equipment originating in the Soviet Union and recently confiscated off the East Coast of the United States. This Soviet surveillance equipment was found by fishermen and was turned over to the Defense Department. Engineers in the Defense Department dismantled the equipment and discovered that the microchips used in the equipment were American in origin. Thus, it appears that our technological advances are being stolen by the Soviets to provide components for their most sophisticated surveillance equipment. Although science education may not prevent international crime, excellent science education may, at least, motivate foreign governments to desire American technological expertise.

A threat to science education in the United States is a threat to our national security. When science education became a national concern we dramatically upgraded our science education programs. Current declining funding for science education research and development comes at a time when we have shortages of qualified computer programmers and engineers. To ensure modern educational programs we must support science education research and development informed by cognitive psychology.

RAPID ADVANCE IN SCIENCE KNOWLEDGE AND COGNITIVE PSYCHOLOGICAL KNOWLEDGE

We need to maintain and expand our expertise in science and mathematics education and our ability to incorporate advances from cognitive psychology. Our science education programs must reflect rapid changes in science knowledge on the one hand, and in *cognitive psychological knowledge* on the other. Our scientific knowledge is rapidly advancing. Similarly, our cognitive psychological knowledge is rapidly advancing. We must continually incorporate these advances into our science of science education programs.

Recent advances in science knowledge include: a) the development of the microchip and the addition of home computers to many households in the United States, b) the synthetic production of insulin and other important biochemical substances, and c) the use of high powered lasers to ignite thermal-nuclear fuel. These and other advances have occurred after a large number of our citizens have taken their last science course and, indeed, have left school.

An important aspect of science education is to develop in our citizenry, the ability to update their science knowledge after leaving school in order to maintain their science literacy. We need a citizenry that seeks and digests information available in magazines such as *Discover*, *Science 82*, and *Quest*, and in books published in the technological area. We might develop science curricula for informal learning environments such as science centers and community education centers. In order to accommodate rapid advances in science knowledge we *must* revise our science education programs for schools.

Rapid advances in cognitive psychology can greatly enhance our science programs. Herb Simon at Carnegie-Mellon

University refers to the recent advances in cognitive psychology as "a revolution" (Simon, 1980). Don Norman at the University of California at San Diego points out that cognitive psychologists are now studying "real learning" as opposed to the sorts of problems that have been studied in the past (Norman, 1981). Psychologists can no longer be accused of focusing on nonsense syllables or the behavior of rats. Cognitive psychologists offer us guidance for teaching complex concepts and real problem solving.

Recent advances in cognitive science include a) chess playing machines which can beat master chess players, b) explanations of complex problem solving such as the behavior required to conduct a medical diagnosis or physics experiment, c) instructional programs which diagnose and respond to individual differences in the rate of learning and in the errors that the learner is likely to make. These advances are critical to our science and mathematics education programs. These findings from cognitive science enable us to rapidly increase our expertise in science and mathematics education.

To maintain our expertise in science education, a national concern, we need continued Federal support for cognitive research focused on issues relevant to science and mathematics curriculum development and teacher education. Our expertise in cognitive psychology is a national resource. We export our expertise: Those in cognitive psychology regularly receive reprint requests and invitations to present their work from the International community. We need, also, to utilize our expertise.

HOW DOES COGNITIVE PSYCHOLOGY IMPACT ON SCIENCE AND MATHEMATICS EDUCATION?

There are two important ways that advances in cognitive psychology impacts on science and mathematic education. First, cognitive psychology provides a framework for a science of science education. Second, advances in cognitive psychology can suggest ways to enhance our expertise in science education.

A Framework for a Science of Science Education

Curriculum development and teacher education efforts will be most successful if they benefit from relevant successes and failures. Only by accumulating our knowledge can we continuously enhance our science and mathematics education programs. Thus, we need to think of science education as a science. The science of science education builds knowledge of how to improve our curriculum efforts and our teacher education programs.

Recent advances in cognitive psychology emphasis the need for more empiricism in science education curriculum development and teacher education. Examples of curriculum development efforts at the Lawrence Hall of Science emphasize the importance of empiricism in curriculum development efforts. Typically, activities developed at the Lawrence Hall of Science go through three to five revisions before they are ready for classroom use (e.g., Health Activities Program Newsletter, 1976-1980). These revisions increase the effectiveness of the materials in fostering learning. We need to apply this model of empirical test and revision to development of new programs, especially programs incorporating recently available technology such as personal computers.

Currently, computers are largely being used for drill and practice in educational programs--far from their full potential. Empirical research is needed to determine how computers can best be used in science and mathematics programs. In teacher education we have developed, over the years, better understanding of how to train teachers. Continued empirical investigations ensure that our teacher education programs are continuously updated.

At the Lawrence Hall of Science we have developed (over the past 20 years) expertise in curriculum development and teacher education by determining which aspects of our programs are successful and which aspects are unsuccessful. We can be seen as engineers of science curricula and teacher education programs in that we tinker with these programs until they become effective educational tools.

The Lawrence Hall of Science has gained expertise in science and mathematics education. First drafts of curriculum materials and teacher education materials are far better than first drafts developed years ago. This expertise also convinces us, however, that curriculum materials, teacher workshop plans, and exhibits for the Lawrence Hall of Science when they are in their first version are indeed first drafts. Like all other first drafts, they are in need of revision. As we develop expertise, we become more, rather than less aware, of the need for revision based on feedback from pilot tests of our materials.

Our gains in expertise in science education mean that we answer some questions and pose new questions. Whereas early science curricula concentrated mainly on presenting the science concepts effectively, we now attend to additional issues and especially issues suggested by cognitive psychologists. Thus, we can pay attention to tailoring our activities to differences in students. We are able to provide, within the science and mathematics community, opportunities for students who learn at different rates to gain from the program. In addition, we can provide ways to tailor activities to the needs of handicapped students. Similarly, in the area of teacher training, we can not only train teachers to consider the characteristics of learners in providing instruction but also we help teachers to recognize which learners are in need of help and to diagnose the type of help that is likely to be needed. For example, we can help teachers recognize the errors or misconceptions their students are likely to have. Thus, our expertise in the area of science education, informed by cognitive psychology, enables us to consider more difficult problems than we were able to consider in the past.

Advances in Cognitive Psychology Important for a Science of Science Education

Cognitive psychology provides us not only with a framework for a science of science education but also with research findings which can rapidly enhance our expertise in the science of science education. This expertise enhancement occurs because we use clues from cognitive psychology to guide our science of science education.

Cognitive psychology and the science of science education enhance each other. Cognitive scientists frequently select problems from science education which have perplexed science educators (e.g., Siegler, 1976, Proportional Reasoning). Similarly, science educators pay attention to cognitive scientists because cognitive scientists have addressed issues in problem solving, such as planning, which are also of concern to science educators. These two fields provide important evidence for each other.

Three categories of input from cognitive psychology suggest how cognitive psychology can impact on the science of science education. First, well-documented findings from cognitive psychology are useful for science educators.

Second, current research in cognitive psychology can impact on science curriculum development. Third, certain problems in cognitive psychology could, if resolved, greatly enhance the science of science education.

Well Documented Findings From Cognitive Psychology

Many well-documented findings in cognitive psychology are of great interest to curriculum developers and teacher educators. One advance concerns the limitations on human processing capacity. In 1956, Miller suggested that humans are able to process about seven things simultaneous, referring to "the magic number seven plus or minus two". Miller's message was that human processing capacity is limited. In 1967, George Mandler suggested that the "-2" was more accurate than the "+2" and that in fact, individuals are really likely to process only about five things at the same time. By 1981, Herb Simon suggested that humans could only process about two chunks of information at the same time, and that this limitation appeared to be fairly universal from one problem to another. Limitations on human processing capacity are well established -- hopefully the downward trend is definitional.

Whatever the limitation of human processing capacity, its existence is important for those designing curricula and providing teacher education materials. Science-curriculum developers and teacher educators are concerned with the limitation on human processing capacity. During tests of curriculum materials and teacher education materials, LHS staff frequently focus the presentation on only the most essential information, and on whether recipients can comprehend the intended message. Trials determine how much information overloads the processing capacity of program recipients.

Examples of curricula that overload the human information processing system abound. Clearly, understanding of human processing capacity limitations requires more widespread attention. We need better ways to present complex information without creating overload. Cognitive psychological research has suggested issues, such as processing capacity, which help developers streamline the development process.

Recent Findings from Cognitive Psychology

Specification of processing procedures used by problem solvers, a recent trend in cognitive psychology, has broad implications for a science of science education. Researchers have characterized how learners construct the knowledge they display. This research tells science curriculum developers and teacher educators why learners develop alternative conceptions of phenomena and events and explains why these alternatives often persist in spite of contradiction.

Researchers following the information processing perspective develop understanding of the performance of individuals *while* they solve problems. This approach includes consideration of problem solvers' errors, behavioral responses, such as eye movements, and verbal responses, such as "thinking aloud". All of this information is considered in explaining how the problem solver approaches and proceeds in resolving the problem. Frequently, computer simulations are used to validate information processing hypotheses suggested by the cognitive psychologists. This approach is especially useful for science educators because it gives considerable insight into how learning proceeds and how interventions might be viewed by the learner.

An important factor, when learners construct knowledge of a situation, concerns the role of beliefs and expectations. For example, in research on the ability to control variables (Linn & Swiney, 1981; Linn, Clement, & Pulos, in press; Karplus, Karplus, Formisano, & Paulsen, 1977) researchers find that most adolescents can sometimes conduct controlled experiments but do not always conduct controlled experiments. A controlled experiment occurs when the variable under investigation is changed and all other variables are kept the same in two trials. So, adolescents might control variables when designing an experiment to determine which of two toothpastes is the best, but not control variables when determining which of two rods bends the most.

Linn and Swiney (1981) found that *beliefs* influenced the unevenness in performance because individuals controlled the variables that they thought were important. For example, in experiments having to do with the expansion of springs, respondents were more likely to control the weight hung from the spring than they were to control the material which the spring was made from. Frequently, subjects indicated that they didn't think the material was important because all the springs were in fact made of metal. Examination of the errors that the students made and their explanations for the errors indicated that <u>belief</u> in the importance of the variable explained why they controlled variables in some situations but not in others: They controlled the variables they believed were important.

Another important aspect of how reasoners construct knowledge is that reasoners develop alternative conceptions for phenomena, they do not respond capriciously. An example involves Predicting Displaced Volume. The task is illustrated in Figure 1. In this task, subjects are told that there are two metal blocks, both of which sink when immersed in water. They are asked to predict which of the two blocks will displace the most liquid when immersed in water. A typical student (referred to as John) responded as illustrated in Figure 1. What alternative conception is John using to predict which of the two metal blocks will make the water go up higher?

Figure 1 about here

John's responses indicate that his alternative conception is "The greater the weight of the solid immersed in water, the more liquid it will displace." Thus, John uses what we refer to as the weight conception for predicting how much water will be displaced. For a more detailed discussion of this task, and the alternative conceptions used by subjects, see Linn and Pulos (1981).

Another typical student, referred to as Susan, responded as shown in Figure 2. Susan's conception is more complex than John's. Essentially, Susan's conceptions is: "If the blocks differ in size, then the bigger one makes the water go up higher, and if the size of the blocks is the same, then the heavier one makes the water go up higher". Linn and Pulos (1981) frequently found this response among twelve- to sixteen-year-old adolescents.

Figure 2 about here

Information processing research helps us understand that learners generate alternative conceptions rather than simply wrong answers. John's and Susan's responses to the Predicting Displaced Volume task tell us how they each solve the problem. Generally, students are consistent in their responses. Susan and John are not just wrong about what factors influence Predicting Displaced Volume, each have consistent alternative conceptions for Predicting Displaced Volume (alternatives to the correct answer that the volume of the block is the only factor which influences how much liquid is displaced). If the educational program attempts to remediate each of these and other common alternative conceptions, the instruction will be enhanced.

Why do learners have alternative conceptions for Predicting Displaced Volume? In general, their beliefs about weight contribute to their performance: they expect weight to be influential when it is not. Weight is often a variable in other domains. Individuals solving Predicting Displaced Volume may use an improper analogy and expect that weight is important in Predicting Displaced Volume because it is also important in how far an object moves when hit by another object or how much one's toe hurts when something is dropped on it. Thus, individuals may have beliefs about the role of weight which they bring to this situation. The role of alternative conceptions and of beliefs which relate to them deserve serious consideration in the planning and execution of science education curricula and teacher materials.

Is it easy to alter the students' expectations concerning the role of weight in Predicting Displaced Volume? If teachers demonstrate that weight is not a variable in this situation do most students accept this pronouncement and move on to the next task? Evidently not. Predicting Displaced Volume is a topic in most science curricula in 7th and 8th grade, yet over 50% of 12th grade respondents to this task use an incorrect alternative conception which involves weight in some respect (Linn & Pulos, 1981).

We conducted an investigation to test the role of instruction in changing respondents' conceptions of Predicting Displaced Volume. We demonstrated how much water was displaced by solids of varying size and weight in about ten minutes of instruction for subjects who initially used a weight based alternative conception for solving Predicting Displaced Volume (Pulos, de Benedictis, Linn, Sullivan, & Clement, 1982). One subject, when confronted with a contradiction to the weight conception responded: "Humm, the water went up the same in both the containers even though one of those cylinders weighs more than the other. You must have magic water."

This subject felt that the experimenter was being tricky and using water that didn't have the usual properties. The subject believed that weight was an important factor and was willing to suggest that the experimenter was using magic water in order to defend the role of weight in Predicting Displaced Volume. It should be noted that tenacious defense of erroneous ideas has proved valuable in the history of science (Lakatos, 1972), so tenacious defense of ideas concerning a scientific phenomena may not be totally inappropriate. However, in Predicting Displaced Volume, weight does not determine displacement. This view needs to be remediated so the individual can pursue other questions.

How can identification of alternative conceptions and of the role of beliefs in problem solving help develop the science of science education? Investigations which illustrate subjects' information processing procedures provide teachers with better insight into how their students might perform in the classroom. In the Predicting Displaced Volume example, students' alternative conceptions are consistent. These students are not just wrong, they actually have a set of alternative conceptions and beliefs which have worked for them in many situations and which they tenaciously protect. Susan's conception, for example, actually works quite well in helping her predict how much volume will be displaced. Only when two solids of equal size but unequal weight are presented can we discern that Susan, in fact, has an alternative conception for Predicting Displaced Volume. Teachers need to be aware of alternative conceptions in order to provide instruction that focuses specifically on the errors that students are likely to make. Curriculum developers need to incorporate attention to beliefs and to alternative conceptions to provide effective materials.

Likely Concerns of Cognitive Psychology

There are important unanswered questions in cognitive psychology which, if answered, could greatly enhance science education. For example, cognitive psychological research could impact on science education by understanding the organization of intellectual structures in the mind. The organization of intellectual structures determines how the individual comes to select certain information and not other information in solving a problem. Questions include, how do individuals decide which information is relevant to a problem? and How do individuals add new knowledge to their ideas? Organizations of intellectual structures are of current interest to cognitive psychological researchers. Researchers are grappling with these questions and have put forth a number of ideas which may eventually impact on a science of science education.

For example, many researchers have considered the role of experience in the organization of the intellect. Simon, in studying how expert chess players solve problems, has modeled how chess experts use experience in computer simulations of chess playing. His hope was that this model might enhance the chess playing capability of the computer. In attempting to build this model, Simon has uncovered ways of representing the relationships among intellectual structures and the role of experience in the forming of these relationships. However, his experiments are only a first step in understanding this important problem.

Similarly, Piaget has grappled with the role of experience in the development of intellectual structures (e.g., Piaget, 1971, 1977). Piaget suggests that the maturing individual comes to abstract strategies from experience. However, Piaget acknowledged that this experience was neither necessary nor sufficient for the development of intellectual structures. Piaget recognized the importance of this problem and offered some insight, but not a solution to the difficulty.

Other approaches to understanding of how the brain organizes information come from the study of neuroscience. Ultimately, in order to answer this question, collaboration among neuroscientists, cognitive psychologists, and those studying the acquisition of specific knowledge, such as science educators, will be required. Answers to this question will offer important insight into how we conduct science education. Clearly, science education which fosters efficient organization of the mind, would greatly enhance productivity and science literacy. Thus, research on the organization of the mind could ultimately have a profound impact on a science of science education.

SUMMARY

Science education is a national concern; our national defense depends on the effectiveness of our science education programs. Our expertise in a science of science education is a national resource. A threat to science education is a threat to our national security.

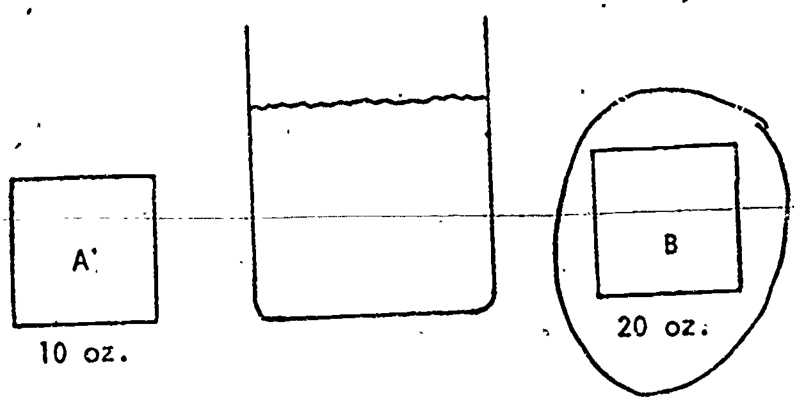
To maintain and enhance this national resource, we need to enhance our empiricism in the science of science education by incorporating findings from cognitive psychology into our science of science education. Findings from cognitive psychology have impacted on science education; current issues in cognitive psychology will ultimately enhance our understanding of science education. We need science educators concerned with findings in cognitive psychology to incorporate these advances into a science of science education.

Figure 1

Water Glass Puzzle: John's Response

Note: John was told that all blocks sink
and are completely covered by water

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



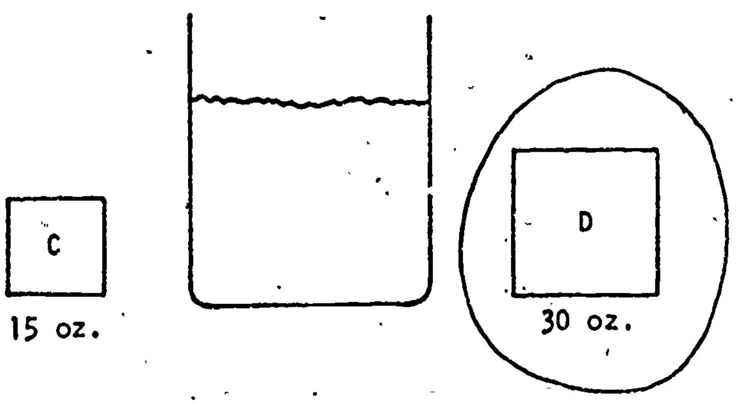
Which block will make the water go up higher?

Block A

Block B

Both the same

2. Block C is smaller than Block D. Block D weighs more than Block C.



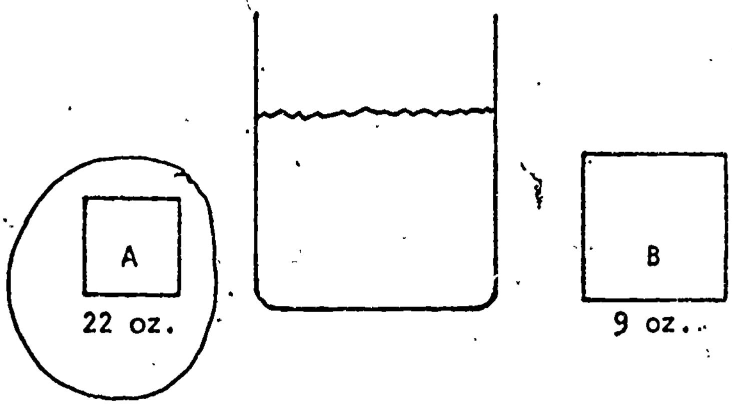
Which block will make the water go up higher?

Block C

Block D

Both the same

3. Block B is larger than Block A. Block A weighs more than Block B.



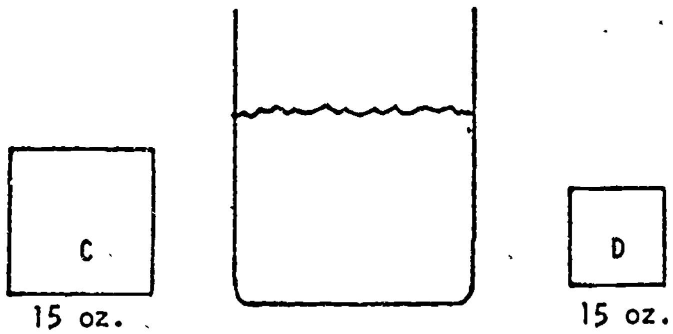
Which block will make the water go up higher?

Block A

Block B

Both the same

4. Block C is larger than Block D. Both blocks weigh the same.



Which block will make the water go up higher?

Block C

Block D

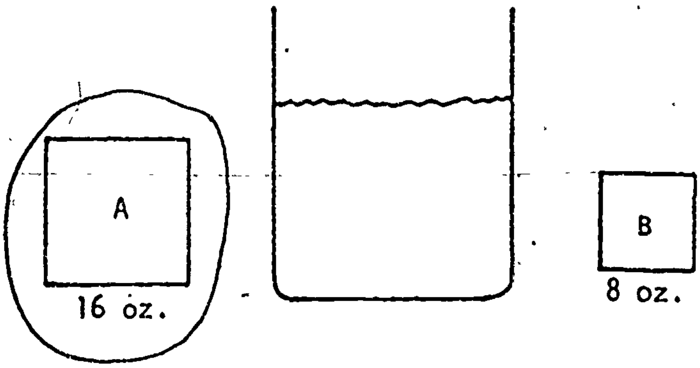
Both the same

Figure 2

Water Class Puzzle: Susan's Response

Note: Susan was told that all blocks sink and are completely covered by water

5. Block A is larger than Block B. Block A is heavier than Block B.



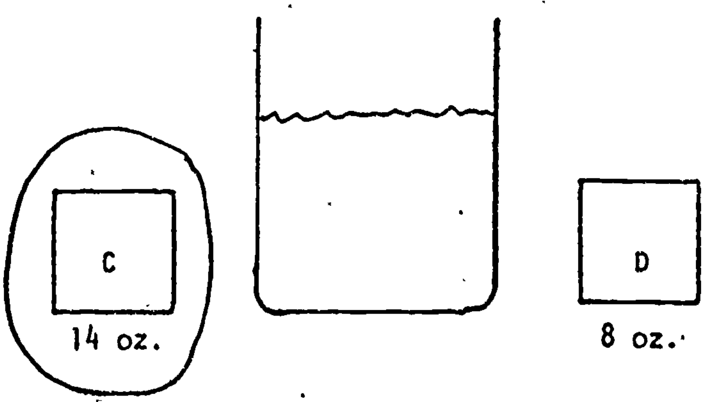
Which block will make the water go up higher?

Block A

Block B

Both the same

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



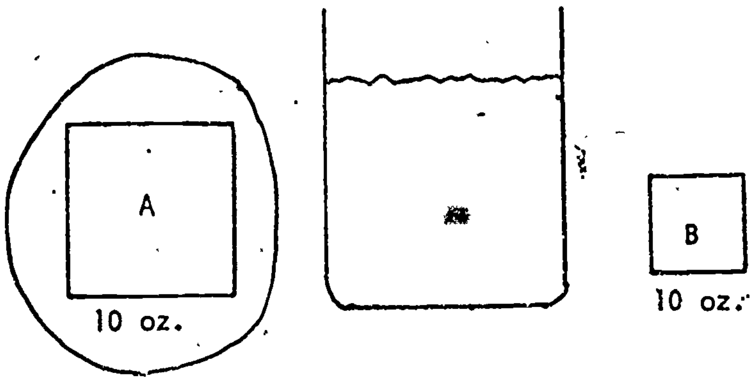
Which block will make the water go up higher?

Block C

Block D

Both the same

7. Block A is larger than Block B. Both blocks weigh the same.



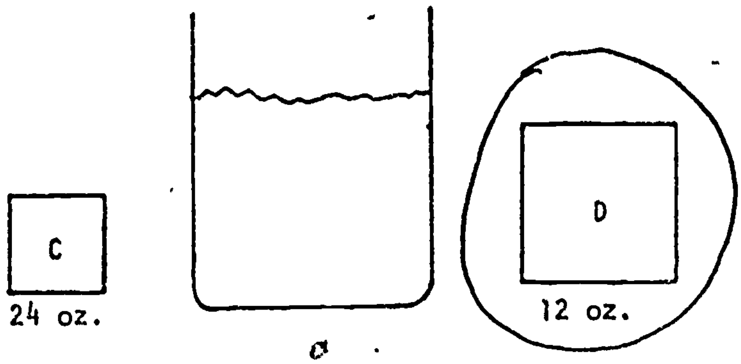
Which block will make the water go up higher?

Block A

Block B

Both the same

8. Block D is larger than Block C. Block C weighs more than Block D.



Which block will make the water go up higher?

Block C

Block D

Both the same

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