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ABSTRACT

This paper summarizes a report designed to provide the National Science Board Commission with information about recent advances in cognitive/behavioral science relevant to mathematics, science, and technology education, as well as prospective contributions from these fields if adequate levels of support are available. Following a summary statement, the report is organized into four sections: introduction; findings of recent research; research needs and opportunities; and structures for application and support. The first section focuses on two areas: problems of educational content (what to teach students so they can be effective in solving problems and reasoning about significant issues; what to teach about technology; and the role of basic mathematical and programming skills in the curriculum) and problems of increasing student participation in mathematics, science, and technology programs, and of increasing effective use of technological resources (including educational testing). Several examples (relating to physics text problems, arithmetic word problems, misconceptions, and others) are presented. Findings from recent research (section 2) and research needs (section 3) focus on the two major areas (content and participation problems) discussed in section 1. Conditions considered important for continued development and the use of scientific knowledge in cognitive/behavioral sciences relevant to mathematics/science/technology education are discussed in the last section. (JN)

REPORT TO

NSB COMMISSION ON PRECOLLEGE EDUCATION

IN

MATHEMATICS, SCIENCE AND TECHNOLOGY

"RESEARCH ON COGNITION AND BEHAVIOR RELEVANT TO EDUCATION IN MATHEMATICS, SCIENCE, AND TECHNOLOGY"

THE FEDERATION OF BEHAVIORAL, PSYCHOLOGICAL, AND COGNITIVE SCIENCES

April 1983

SUMMARY

This paper summarizes a report based on a hearing organized by the Federation of Behavioral, Psychological, and Cognitive Sciences for the National Science Board Commission on Precollege Education in Mathematics, Science, and Technology. The purpose of the report is to provide the NSB Commission with information about recent advances in cognitive and behavioral science relevant to education in mathematics, science, and technology, as well as prospective contributions from these fields if adequate levels of support are available. In this summary paper we discuss some of the major recent contributions and topics for further fruitful research that are considered in the full report.

The need for strengthening our nation's educational programs in mathematics, science, and technology is now recognized by almost everyone. Significant resources must be directed immediately to reducing the critical shortages of qualified teachers of mathematics and science in our elementary and secondary schools.

At the same time, some important problems cannot be solved by the use of educational methods that are currently available. A higher level of technical knowledge and skill is required for productive employment and for effective citizenship than has been the case in the past, and these demands will continue to increase. More effective teaching materials and methods are needed to provide an increased number of students with knowledge and skill for problem solving and reasoning based on scientific, mathematical, and technological subject matter. Improved understanding of processes of problem solving, comprehension, learning, teaching and testing is needed to guide the development of new educational resources, including effective use of new computational technology that is becoming available for use in instruction and testing.

American education has benefited in fundamental ways from basic research in behavioral and cognitive science. Important examples include concepts and methods of behavioral task analysis that have been used in formulation of objectives for instruction and testing, as well as psychometric methods used in developing and evaluating tests of ability and achievement. Research on these and other topics continues to provide important empirical and theoretical contributions to our understanding of educational processes.

Recent scientific developments, especially in the analysis of cognitive processes, have special relevance for education in mathematics, science, and technology. These developments in theory and methodology have provided significant new insights into students' processes of solving problems and understanding concepts. These findings provide significant opportunities for development of improved educational methods in mathematics and science, and continued scientific investigation based on these recent findings promises to provide further knowledge relevant to important educational questions.

Recent Findings

We present brief summaries of some recent findings that illustrate the relevance of behavioral and cognitive research to education in mathematics, science, and technology.

An important topic in recent research has been qualitative cognition, involving processes and structures needed to use and understand formal procedures and principles. At present, instruction in mathematics, science, and technology emphasizes quantitative procedures and formulas that express principles. Formal knowledge alone is inadequate if students are to be able to solve problems using their scientific or mathematical knowledge, or to achieve correct understanding of the principles represented by the formulas and procedures that they learn. Scientific study of problem solving, reasoning, and learning has provided important new information and theoretical understanding of knowledge structures that are required for successful use and understanding of formal knowledge.

One form of qualitative cognition involves knowledge used for understanding problems in science, mathematics, and technology. When students are required to solve problems that are presented using text and diagrams, cognitive representations of the information in the problems must be constructed by the students. Substantial results have been obtained regarding knowledge structures needed to represent problems in physics, in elementary arithmetic, and in electronics; theoretical representations of these structures have been developed in the form of schemata and mental models. Research has begun on development of instructional methods that can increase students' skills in representing problem information.

Another form of qualitative cognition involves functional understanding of procedures that are used in solving problems. Recent research has shown that general concepts and cognitive procedures can be integrated and mutually reinforcing, and ways in which such integrated knowledge can be produced in instruction are being investigated. In debates about computational skill and conceptual understanding such as those surrounding the "new math," skill and understanding have been considered as competing alternatives. In the view that is now emerging from research findings, there are general functional concepts and principles corresponding to critical relationships among components of task situations and the procedures that are used in the domain. Analyses of these functional principles have been provided in elementary arithmetic and high-school geometry; these analyses have begun to show how understanding of general concepts can facilitate learning and performance of correct procedures in addition to providing meaningful understanding of the procedures.

Research in the domain of physics has shown that students begin with significant misconceptions of general principles involving qualitative conceptions that they apply in understanding physical phenomena. These tend to persist through their instruction, so that their qualitative understanding of principles is inconsistent with the significant principles on which the formulas they have learned are based. Instructional methods that take students' prior conceptualizations into account have been investigated.

Research also has identified factors that influence students in selecting courses in mathematics and science, particularly among young women and members of minority groups. In addition to achievement in previous educational experiences, individuals are more likely to participate in mathematics and science education if they perceive these fields to be relevant to careers that are available to them, and if they have a general interest in "things," rather than primarily in "people." Contrary to some popular belief, exposure to female role models in science and mathematics has been found to have little effect on young women's decisions to participate in science and mathematics education.

Needs and Opportunities for Research

Results of recent research can be used now to guide development of new instructional materials and methods. Enough is known to provide a sound basis for design of instruction to provide improved skill in representing problem situations and stronger functional understanding of formal procedures and principles, and to take account of students' preconceptions and interests.

Research findings have shown that knowledge for understanding problems, functional understanding, and mental models are essential cognitive components for effective learning and performance. Better understanding is needed of how these aspects of cognitive structure facilitate cognitive performance and learning.

A great deal is now understood about knowledge required for solving problems in individual domains, bur there are significant unanswered questions about the kinds of cognitive structures and processes that enable knowledge acquired in one domain to be applied in another. An important aspect of this question involves the nature of general skills for problem solving, reasoning, and learning, and whether cognitive skills with significant generality can be acquired through instruction. Analyses of transfer in some domains have shown that qualitative understanding of principles can provide a basis for significant transfer. Research is needed also to identify instructional materials that provide students with knowledge and skills that they require for productive employment and meaningful citizenship in an increasingly technological society. Progress has been made in understanding learning of basic components of problem-solving skill. We do not yet understand learning of strategic knowledge, knowledge for representing problems, and procedural knowledge integrated with functional principles. Principles that are discovered in these studies of acquisition will be useful in design of instructional materials and methods of assessment, which also can take account of students' preconceptions and interests related to the subject matter, and exploit resources that are available because of advances in computational technology.

Structures for Support and Application

Recent developments have brought about a significant strengthening of America's resources for scientific research relevant to education in mathematics, science, and technology, as numerous scientists have turned their attention to processes of problem solving, reasoning, and learning the specific subject-matter materials of these fields.

Research on problems relevant to education in mathematics, science, and technology benefits from close collaboration among behavioral and cognitive scientists, mathematicians and scientists in the fields being taught, and educators.

An important condition for application of research findings is their communication to teachers, and strong efforts should be made to include up-to-date scientific knowledge about cognitive and behavioral processes in in-service and preservice teacher training programs. Research programs in which classroom teachers participate as collaborative scientists can play an especially helpful role, both in informing the research effort by direct acquaintance with the teaching context and providing the occasion for participating teachers to become directly familiar with research methods and results.

FORWARD

This report is based on materials presented at a hearing sponsored by National Science Board Commission on Precollege Education in Mathematics, Science, and Technology, held at Pittsburgh on 19-20 December, 1982. The hearing was organized by the Federation of Behavioral, Psychological, and Cognitive sciences at the invitation of the Commission. The following individuals participated in the hearing:

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I. Introduction

The nature and purposes of education in mathematics, science, and technology are undergoing significant change. All children and youth, and an increasing number of adults in our country, now face educational requirements that demand previously unanticipated forms of competence. The level of knowledge and skill expected of individuals has risen sharply as a result of the demands of technological change for new knowledge and skill. In view of these changes, there may now be diminishing returns in continuing to employ the curricula and school practices that have effectively increased general educational levels in the past.

Toward the solution of this critical problem, we discuss contributions that past and forthcoming research in cognitive and behavioral science make to education in mathematics, science, and technology. We describe recent research findings that have important implications for the design and practice of education in these fields. We also discuss research questions that have strong potential for providing important further empirical and theoretical advances relevant to the improvement of educational practice.

A major recent scientific development is the growth of cognitive science, an interdisciplinary field that includes components of psychology, computer science, linguistics, anthropology, and education. It is important to emphasize that the development of cognitive science in the United States is substantially more advanced than in any other country. This provides an opportunity for American education in mathematics, science, and technology to utilize a set of findings for which American scientists have deep understanding, and to benefit further from research advances that can be achieved in the immediate future.

The considerable progress made recently in the cognitive sciences provides powerful new concepts and methods for approaching educational tasks in more systematic and scientifically principled ways.

<u>The central scientific advance has been development of the capability to analyze the cognitive requirements for successful performance in complex intellectual tasks.</u> This has been accelerated by new techniques that specify hypotheses about cognitive processes and knowledge structures that are the basis for successful human performance in the form of computer programs. This helps ensure that theoretical descriptions reach a level of detail that is adequate to explain performance and to provide guidance for instructional design.

The important outcome is an improved capability for analyzing students' understanding of concepts and principles of mathematics, science, and technology and to relate their understanding to their ability to perform successfully in instructional tasks. This has led to new insights into the educational effects of such issues as meaningful vs. rote learning and the importance of well-structured knowledge in acquiring new cognitive skills. These developments provide a considerable advance beyond earlier research and development in psychology and education. Specific analyses of cognitive processes and knowledge structures have been used to compare the knowledge and skills of experts with those of beginning students, providing a basis for more definite and useful specification of objectives for instruction. Analyses of students' knowledge prior to instruction and of errorful procedures and misconceptions that result from some instruction have provided new understanding of sources of students' difficulty in acquiring cognitive skills and knowledge.

Our scientific capabilities now enable us to analyze knowledge that is required for success in tasks used in mathematical, scientific, and technical instruction. Examples of subject-matter domains in which specific cognitive task analyses have been contributed include elementary arithmetic, algebra, high school geometry, mechanics, hydrostatics, and elementary electricity/electronics. We will describe results of some of these studies in Chapter II of this report. It is important to note that a substantial number of scientists are now studying these topics, providing a valuable resource of talent and experience for continued research and scientific training.

Most previous efforts at improving science education in the United States were directed at curriculum development together with some associated teacher training. In particular, the various major curriculum-development projects of the 1960's attempted to introduce into schools points of view and conceptual approaches reflecting those of expert scientists or mathematicians. Although these efforts were laudable and partially successful, their ultimate educational impact and effectiveness were far less than had been hoped. One of the principal reasons for this failure was that the educational reformers focused their attention almost exclusively on curriculum content, thereby failing to pay adequate attention to important psychological aspects, the underlying thought and learning processes of students or experts and underlying social-psychological processes in the classroom. Our scientific capabilities for investigating these psychological processes have been greatly strengthened by the recent conceptual and methodological advances in cognitive science.

In the past, educational methods and materials based on fundamental research in behavioral and cognitive psychology have had profound effects on American education. The use of standardized tests, both for assessment of students' learning achievement and for selection for college and professional training, is based on psychometric methodology developed in psychological research that began early in this century. Principles of behavioral task analysis, based on fundamental research on learning and conditioning, have been used in formulating educational objectives, and have had strong influence on the design of instructional materials and tests. Rigorous application of such principles in the early grades is now producing heartening improvements in the school achievement of many inner city students. Little of education in this country has been untouched by these earlier scientific developments.

Research on many topics of behavioral and cognitive science, as well as other fields, continues to provide significant findings of importance for educational practice. In this report, we discuss a subset of the important research that has been done, focussing on studies that have dealt directly with processes of thinking and learning in the domains of mathematics, science, and technology. It is important to keep in mind that science is an ongoing process, so that important aspects of our current understanding will undoubtedly be replaced by concepts and principles yet to be discovered. Furthermore, any domain involving application of theoretical principles and scientific knowledge always involves a balance of current theory with practical wisdom. Even so, the potential for strengthening American education on the basis of past and prospective research in cognitive and behavioral science is strong.

I.A. Some Problems of Education

Our presentation of research findings and questions in Chapters II and III is organized by two major types of problems that face our educational system in regard to mathematics, science, and technology. First, there are problems of educational content: what to teach students so they can be effective in solving problems and reasoning about significant issues; what to teach about technology; and the role of basic mathematical and programming skills in the curriculum. Second, there are problems of increasing the participation of students in programs of mathematical, scientific, and technological education, and of increasing the effectiveness of the use of technological resources, including educational testing.

I.A.1. Questions of Educational Content. A major goal of education is to provide mathematical, scientific, and technological literacy. Students should acquire the ability to solve problems and reason effectively in a broad range of situations that arise in their lives and work. The relevant question is whether the knowledge and skill that students acquire in the present curriculum provide as strong a basis as possible for general problem solving and reasoning.

Students in mathematics and science often learn computational procedures and formulas that they are unable to apply in solving problems or in reasoning about qualitative questions. Recent research has provided improved understanding of the cognitive requirements of successful problem solving and reasoning in a variety of academic and practical domains, and these findings indicate a need to emphasize some aspects of knowledge not now emphasized in mathematics and science instruction.

The growing role of technology, especially computational systems, in human affairs implies a critical need for education that prepares students to understand and use technological resources. Recent research has provided information about properties of knowledge required for understanding technical systems such as electronic devices and power plants, and these findings suggest important issues for the development of education for technology.

The role of "basic" skills such as computational procedures in mathematics and interpretation of experimental data in science, is a question of long standing in the design of instruction, and computer programming is emerging as another skill that many believe all students should acquire. Results of recent research have advanced our scientific understanding of the kinds of conceptual knowledge and knowledge for representing problem situations that facilitate students' learning of correct procedures and their ability to use their formal knowledge in solving problems and reasoning.

I.A.2. Questions of Participation and Effectiveness. Economic and technological changes in the society are producing an increased need for individuals whose basic education in mathematics and science prepares them for advanced training in technologically demanding fields. A relatively high level of technological literacy is needed for successful performance in a great many work environments, and for informed participation in the formation of public opinion on critical policy issues. We need improved methods of education to enlarge the group of students who learn mathematical, scientific, and technical subjects successfully.

Recent research findings provide significant new information about sources of difficulty in learning and understanding mathematical, scientific, and technical concepts, and thus provide a basis for educational materials and methods that can reach a broader group of students. Research has also begun to identify factors contributing to relatively low levels of participation in mathematics and science courses by women and members of minority groups, and thus suggests ways in which increased participation by those individuals, and indeed all persons, can be encouraged.

The potential impact of new information technology on education is widely recognized, as is the need for research and development to enable its beneficial use. This is especially significant for education in mathematics, science, and technology, where the need to provide soundly based computer-augmented instruction is becoming critical. Cognitive and motivational properties of computer-based instructional systems have been studied in recent research, and the findings provide guidance for the design of instruction with computers and other media.

Data in the form of test scores are an important source of information about the success of our educational programs, and they play an important role in assessing individual student achievement and selecting individuals who are most likely to succeed in advanced and specialized training. The design of tests is influenced strongly by theories of the cognitive abilities or knowledge that is being assessed, and recent research has provided advances in our understanding of the characteristics of general and specific cognitive skills that effectively indicate successful performance on tests of achievement and aptitude. Tests also have a considerable influence on the shaping of instructional content; thus, it is important that new understanding of instructional goals should be reflected in new approaches to testing.

I.B. Introductory Examples

We present a set of research findings that have been obtained recently, primarily in the last five years. These findings, their implications for education in mathematics, science and technology, and some prospective research to build on present knowledge, are discussed here to illustrate the kinds of results and conclusions that are characteristic of recent research. In Chapters II and III we provide a survey of research topics and findings in which the discussion of each topic is very brief; if more specific discussions were provided, they would be comparable to the discussion presented here.

The example research that we discuss here focuses on a common theme of qualitative understanding. Much of the knowledge currently taught in mathematics, physics, and technology is based on quantitative, analytic principles of the domains. These formal principles act as a set of constraints that characterize what happens in a system. Almost by definition, such a characterization provides students with little understanding of the underlying qualitative mechanisms governing how it happens. Said differently, students fail to learn how the formal constraints are necessarily satisfied or even how the requisite behavior emerges from these constraints.

The elegant and concise formal description of diverse and complex phenomena and the use of rigorous systems of deductive inference are major intellectual accomplishments of science. Not surprisingly, they are displayed and emphasized in the curriculum. However, it is now widely understood that formal knowledge of mathematics and science is not sufficient in itself for effective use of the knowledge or for intellectual work that advances the fields of knowledge. Scientists, mathematicians, engineers, and technical workers commonly recognize that their "textbook" knowledge must be supplemented in significant ways for them to be effective in their work. The characteristics of the additional knowledge and skill needed for effective work have not been understood, beyond the truism that they are probably acquired in practical experience, rather than in formal instruction. (It could hardly be otherwise, since the additional knowledge and skill are just those necessary cognitive components that are omitted from formal instruction.)

In recent research, several findings have been obtained that provide significant new insight into knowledge and skill that involve qualitative principles in mathematics, science, and technology. With these findings, we can begin to specify the characteristics of qualitative understanding in definite ways, and to specify the ways in which that understanding functions in problem solving, reasoning, and learning.

A key idea that has emerged from this work is that knowledge of qualitative principles enables an individual to construct mental models of how a system or a procedure "works." These models, in turn, form the bridge with much of the individual's common-sense understanding of the world, in both physical and social aspects. But these mental models do more. For the theoretically inclined student, this kind of knowledge provides the basis for guiding his or her intuitions concerning how to construct precise mathematical models of a given phenomenon, as well as how to make sound approximations in solving the equations comprising the analytic models.

For technicians or maintenance personnel, these qualitative, causal models provide the basis for fomulating defensible hypotheses for explaining observed malfunctions of a system or a machine. This kind of knowledge enables the technician to construct simulations "in the mind's eye" of how a system functions and to use the constructed causal models to guide his or her common-sense reasoning and troubleshooting strategies. That is to say, with such models, the individual can develop a generic understanding of systems and use this understanding to handle novel problems and enable his or her troubleshooting methods to be more than just rote procedures.

Research advances have been accomplished in two areas: the role of qualititative understanding in problem solving, and its role in learning.

I.B.1. Qualitative understanding in problem solving. Research investigating the detailed nature of problem solving in several domains has provided significant new information about the cognitive processes and knowledge that are needed to use the formal knowledge of science and mathematics. Typically, in mathematics and science teaching, formulas and computational procedures are explained directly, but use of those formal procedures for solving problems is treated implicitly, using examples but little or no direct instruction about problem-solving methods. Recent findings have shown some of the kinds of knowledge that are required for successful problem solving, and have provided explicit descriptions of that knowledge relevant to selected domains in mathematics and science. As we develop explicit characterizations of knowledge required for problem solving, it will become possible to provide instruction that trains that knowledge more directly, and as a result we should expect greater effectiveness in teaching problem-solving capabilities.

Arithmetic word problems. Knowledge required to solve simple arithmetic word problems has been studied in detail, and a complete analysis is available for problems that are solved with addition and subtraction. To solve these problems, students must form intermediate representations that include relationships among the quantities in the problems. To form these representations, students must learn to recognize three distinct patterns that involve different ways in which quantities can be related. These patterns correspond to groupings of problems that are fundamentally the same beneath their varying surface details. The technical term for such underlying patterns is schemata. For simple arithmetic problems, these underlying patterns have now been identified and described. One of these, a Change pattern, involves an event that increases or decreases the value of some quantity. A second pattern, Combination, involves two quantities that do not change, but are considered both separately and in combination. The third pattern, Comparison, involves two quantities and the difference between them. Models of the problem-solving process have been formulated to show how recognition of these patterns is needed, and depends on knowledge in the form of schemata, cognitive structures that include the relationships in general form. The models have been tested in detailed observations of performance of children as they solve problems, and have provided explanations of different levels of skill that are observed among elementary school children.

Physics text problems. Several investigators have conducted research on processes of solving text problems in physics. A detailed analysis has been formulated as a simulation model for solving statics problems. Knowledge that is required includes schemata for representing relevant quantities and their relations in problem situations; for example, to solve a problem about a man standing on a ladder leaning against a wall, the representation can be formed by assembling a wall schema (surface), a floor schema (surface), a ladder schema (lever), and a man schema (mass), assigning to each component appropriate numerical quantities and appropriate connections with the others. Research also has been conducted in the domain of elementary electronics, and it was found that a major source of difficulty in solving course problems was due to inadequate acquisition of knowledge for representing problems including general relations among quantities.

In addition to specialized knowledge about physics problem situations, problem solving requires use of general causal knowledge about motion of objects and other physical factors. Solution of problems in kinematics has been analyzed, and often includes representation that uses a "mental model" of the objects and surfaces in the problem to determine the set of variables and formulas that have to be used to obtain the solution.

Research findings have been obtained regarding the knowledge used by expert physicists in solving text problems, compared with the knowledge used by successful students with a year or two of study. The problem representations constructed by experts are based on knowledge that is organized by abstract physics concepts and principles, such as the conservation of energy, that furnish the representations for general methods of problem solution. Students' representations are based on more concrete features of problems, showing that their knowledge of general principles is not yet integrated with their problem-solving knowledge.

Implications for education. With more specific scientific understanding of the knowledge required for successful problem solving, instructional methods can be designed to more effectively provide students with knowledge for problem solving. Materials for modifying and expanding the student's approach to representing problems have been developed and are being tested in current research. Materials for teaching kindergarten children to represent some of the relationships found in word problems have been designed and tested as a means of increasing their readiness for primary grade mathematics. Authors of at least one elementary mathematics text series are currently considering ways to incorporate results of research on word problem representation in their instructional materials.

Further research needs and opportunities. The methods and results of research on problem solving in simple mechanics and elementary mathematics can be used to provide comparable analyses of knowledge required for problem solving in other domains. This constitutes an important area of applied research, to provide a basis for development of specific teaching materials for strengthening students' problem solving skills.

Fundamental as well as applied research is needed to investigate processes of acquiring skills in problem solving, including the knowledge for representing problems that has already been identified. Theoretical analysis of learning processes is a major current research topic in cognitive science, and analysis of the acquisition of the knowledge required for representing problems would provide important new theoretical advances as well as information of great practical importance for education. Investigation of fundamental properties of learning necessitates development of experimental instruction to provide the learning experiences to be studied. The materials developed for these experiments will contribute to development and evaluation of instructional materials, which will provide new resources for teaching problem-solving skills.

A major unanswered question is the nature of knowledge that enables transfer of skills acquired for solving problems in one domain to capabilities for solving problems in another domain. Some preliminary findings have been obtained, involving use of general conceptual structures and processes of forming analogical mappings between the domains, but considerable further investigation is needed to provide adequate scientific understanding of this important cognitive question.

I.B.2. Qualitative understanding in learning. Research findings have provided important new information about characteristics of students' qualitative understanding that are relevant to their learning of mathematics and science. Instructional materials and methods rest on assumptions of the students' knowledge prior to the instruction, and if these assumptions are incorrect, instruction is likely to be ineffective, either being too difficult because students are lacking some prerequisite concepts or skills needed for the new learning, or not taking account of conceptions of students that could facilitate or interfere with their learning of new material.

Elementary mathematics. Recent findings require important revisions in assumptions about the conceptual sophistication of children when they enter school. Research by Piaget and others provided general insights into the reasons that many children might have difficulty mastering arithmetic in the early school years. For example, preschool children asked to say which of two sets has "more" objects often respond that there are more in a set that occupies a larger space, confusing spatial and numerical quantity. Although preschool children typically can count sets of objects quite skillfully, it has been assumed that this is an essentially mechanical skill, unaccompanied by appreciation of numerical principles such as cardinality and one-to-one correspondence. Recent research has been giving us a more precise picture of those aspects of numerical concepts that young children do and do not understand. For example, they are able to detect errors in counting performance that they observe, and they can adjust their counting procedures to accommodate novel constraints in ways that preserve principled constraints that make counting correct. Preschoolers clearly have significant components of understanding of fundamental abstract concepts before they begin their formal training in mathematics, a resource upon which instruction can build. On the other hand, other important aspects of number understanding such as the fact that a larger number can be viewed as composed of smaller numbers seem to develop later. This raises the possibility that instruction might be designed to be more effective in promoting such conceptual development.

Recent research also has shown that important conceptual prerequisites for some instruction are not reliably acquired in current instruction. An example is the teaching of subtraction involving multidigit numbers. Principles of the place-value system of enumeration should be understood by children in order for the procedures of column subtraction and borrowing to be understood adequately. A significant number of children do not acquire these principles adequately, with the consequence that numerous children develop incorrect, albeit systematic, procedures for calculation. Theoretical studies have shown ways in which understanding of place-value principles can be used in teaching arithmetic procedures so that they acquire integrated knowledge structures with correct skill and understanding of the constraints of correct calculation.

Preconceptions in physics. A predominant current view underlying curriculum design and teaching in science is that students' understanding of scientific concepts is shaped by their instruction. Much care is taken to avoid presenting incorrect or misleading versions of concepts in order to avoid the need for students to unlearn concepts and principles that are wrong.

Recent research has shown that this view is fundamentally incorrect. Students begin their study of science with strongly held conceptions about the phenomena that are explained by scientific principles, and their preconceptions are often inconsistent with the principles that they are to learn. Furthermore, their informal qualitative conceptualizations often persist after a considerable amount of instruction in science, in which they have acquired formal knowledge based on principles that are inconsistent with their conceptualizations. They may use their formal knowledge correctly to solve textbook problems, but their understanding of events in the world is still based on the conceptualizations that they had prior to instruction.

Examples in physics have been investigated in some detail. Students' preconceptions regarding the motion of objects can be characterized as Aristotelian: for example, they assume that to keep a body in motion a force must continuously be applied to it. When asked about the speed of a falling object at different times after it is dropped, most students answer that it is falling at the same speed at all points in its descent, even though they solve problems correctly using formulas for linearly accelerated motion. Another example involves predictions that students make about the path of an object emerging from a curved tube. They believe that the object will continue to move along a curved path, rather than along the tangent to the curve, indicating an incomplete understanding of the law of inertia.

Implications for education. The view that students learn what they are taught is definitely too simple to be a useful guide for design of instructional materials and teaching. Students do not begin their study of mathematics, science, or technology free of prior concepts that influence their learning. In some cases they begin with significant prior understanding that exceeds the level assumed in current instruction; in other cases their preconceptions interfere with their understanding of the concepts and principles that they are taught.

We need to develop instructional materials and methods that take account of students' existing conceptual understanding, building upon it when it is sound, and bringing about changes in it when it is incompatible with scientific principles. A number of investigators are now studying methods of science instruction that take account of the students' existing conceptualizations.

A new perspective of the relation of basic skills and conceptual understanding is indicated by research on computational procedures. In most pedagogical thinking, skill and understanding are viewed as competitors for scarce instructional resources. Recent findings have revealed forms of understanding that are integral components of knowledge that underlies skilled performance, and that are essential to learning of correct forms of computational procedures. For example, in learning the borrowing procedure in subtraction, it is important to understand that the total value represented by a numeral is not changed when one digit is decremented and ten is added to the digit to its right. These findings indicate that skill and understanding should not be considered as competing alternatives, but need to be provided in ways that reinforce each other in integrated cognitive outcomes of learning.

Further research needs and opportunities. There is a need for research that analyzes learning as a process in which existing cognitive structures are modified by instruction. We need to conduct detailed analyses of effects on learning produced by students' existing implicit understanding of principles and their preconceptions about the subjects they are studying. There is a need for development of instructional materials in various science domains that take account of students' pre-existing conceptions.

We also need to investigate methods of instruction in which formal knowledge of technical formulas and computational procedures are integrated with relevant conceptual structures. There is a need for new systems of mathematical concepts and notation for representing and analyzing conceptual structures, and progress has been made in the development of such formal systems in recent research. Using formal systems for representing conceptual structures that are being developed, we are beginning to have the formal machinery to represent and analyse the kinds of mental models students and experts hold, what the underlying assumptions are, how the technical terms relate to other terms and most importantly, how a person uses these models to predict and/or rationalize a given phenomenon.

The study of mental models per se can be extremely subtle but with improved formal systems for representing conceptual structures we can begin to appreciate the crucial distinctions between seeing a student's view of the world that is faulty (from our perspective) versus really getting inside the student's conceptual framework and understanding what the technical terms mean to the student within the student's framework. Not only is this distinction crucial for being able to effectively remediate the student's faulty knowledge, but it also helps to predict why some faulty concepts are so resistant to remediation. In particular, what often seems incoherent from outside a given framework, makes perfect sense from within the framework, suggesting that local "debugging" of technical concepts might require a restructuring not only of a student's epistemology but also of the student's ontological commitments. For example, if the student views velocity as an intrinsic property as opposed to an (extrinsic) predicate, Newton's first law of inertia will be causally unexplainable. What does it mean to say that students have an Aristotelian view of physics based on their beliefs of inertia? What is their notion of state versus process? Can the Newtonian law of inertia be "accepted" without first viewing both rest and uniform motion as states? This shift from viewing uniform motion as a process to viewing it as a state is profound and the richness of this shift is not easily represented. But the formal systems for representing conceptual structures that are being developed can be used to examine these questions more rigorously and to formulate definite hypotheses about previously vague questions of understanding and representation. Indeed, a major breakthrough in the teaching, acceptance, and use of science might stem from better understanding of how students can move from mental models that are sufficient for everyday reasoning, but are incoherent, to mental models that enable "thought experiments" whose coherence can be examined logically.

II. Findings of Recent Research

This section presents a brief review of findings obtained in recent cognitive and behavioral research of relevance to education in mathematics, science, and technology. To provide the Commission with a sense of the breadth of current work and the numerous investigators conducting the research, we describe each topic briefly, including names of some of the individuals whose research has contributed to that topic, and then mention very briefly a general finding or two that has resulted from the research thus far.

II.A. The Content of Education

The issues addressed in this section involve scientific literacy and general capabilities for problem solving and reasoning in mathematics, science, and technology and specific curriculum questions involving basic skills.

II.A.1. Education for Effective Problem Solving and Reasoning. First we discuss research relevant to the goal of providing education in mathematics, science, and technology that enables students to apply their knowledge effectively in problem solving, understanding, and reasoning in situations that they encounter in both academic and nonacademic settings.

Major scientific advances have occurred involving theories that characterize knowledge that is required for problem solving and for understanding. The theory of problem solving developed in artificial intelligence starting in the 1950's, and use of the ideas for psychological analysis was established by Allen Newell and Herbert Simon in their book, Human Problem Solving, published in 1972. General problem-solving strategies, such as means-ends analysis, were formulated and supported by observations of human performance in solution of problems. The theory of knowledge needed for understanding developed from analyses of language comprehension in artificial intelligence, linguistics, and psychology. Theoretical and empirical advances were contributed by Roger Schank and Robert Abelson of Yale University, Terry Winograd of Stanford University, Donald Norman and David Rumelhart of the University of California-San Diego, and Walter Kintsch at the University of Colorado. Cognitive structures corresponding to knowledge of concepts and their interrelationships have been characterized and hypotheses about processes of understanding have been supported in experiments on comprehension and memory of information in texts.

General theoretical concepts and methods for analyzing problem solving and understanding have been applied in the analysis of cognitive processes used in solving mathematical, scientific, and technical problems. Knowledge underlying students' problem solutions in high school geometry has been studied by Mary Grace Kantowski at the University of Florida, and by James Greeno at the University of Pittsburgh. An important result of these analyses is the characterization of the cognitive basis of students' problem-solving strategies, which have been largely implicit in instruction rather than being presented and taught so that students are aware of them. These strategies involve solution methods that are useful specifically in areas such as geometry that involve the kind of reasoning required in domains with axiomatic structure.

Analyses have also been provided of knowledge required for solution of word problems in arithmetic and algebra. Word problems in elementary arithmetic have been analyzed by Thomas Carpenter at the University of Wisconsin and by Mary Riley of the University of California-San Diego. A major result is the discovery of conceptual structures for understanding relationships between quantities described in problems that are needed for successful solution, and that are distinct from the arithmetic relations of addition and subtraction. These theoretical ideas have been considered by the authors of a series of mathematics texts, led by Joseph Payne of the University of Michigan, and are being used to improve the problem-solving materials in that text series.

Knowledge required for solving problems in physics has been studied by several investigators, including Jill Larkin and her colleagues at Carnegie-Mellon University, Frederick Reif at the University of California-Berkeley, Michelene Chi and her colleagues at the University of Pittsburgh, and Gordon Novak at Stanford Research Institute. These studies, and others in which performance of experts has been analyzed in detail, have provided information about properties of the knowledge base used by experts in solving problems, including basic skills of perceptual encoding as well as recognition of the abstract theoretical principles that are applicable in a problem situation. Research has shown that selection of relevant features and relations and formation of organized cognitive representations prior to the use of solution procedures plays a critical role in successful problem-solving performance. Instruction in physics, as in other subjects such as algebra, emphasizes learning of formulas and procedures that are used in solving problems and neglects teaching the conditions that are required for the formulas and procedures to be appropriate. Research on problem solving has shown the importance not only of knowledge of procedures but also of the conditions for applying problem-solving procedures, and has shown how that information can be extracted from problem situations. Instructional methods based on these basic findings have been developed by Frederick Reif and Joan Heller at the University of California-Berkeley, and preliminary tests of those methods have had quite promising results.

There is now emerging a general theory of broad problem solving competence, including the following components: (a) mastery of basic knowledge and access to relevant facts and procedures in long-term memory; (b) useful problem-solving strategies, many of which now have been described in detail; (c) "control" or "executive" knowledge that good problem solvers use to make efficient use of their resources; and (d) general opinions that students have about the relevance of problem-solving techniques that frequently prevent them from attempting to use methods that they are capable of. Work on this characterization of broad problem solving skills has been contributed especially by Alan Schoenfeld at the University of Rochester.

Some investigators have begun to examine ways in which mathematical knowledge is used in nonacademic settings. These include a study of the use of arithmetic knowledge during shopping by Jean Lave at the University of California-Los Angeles, and a study of the use of mathematics for billing by drivers of milk delivery trucks by Sylvia Scribner at the City University of New York.

II.A.2. Education for Technology. Analyses of cognitive processes and knowledge structures required for problem solving and reasoning in technical domains can be carried out using methods similar to those in basic mathematics and science. Several investigators have studied knowledge and skill involved in electronics problem solving, notably, Gerald Sussman at the Massachusetts Institute of Technology, John Seely Brown at Xerox Corporation, and Mary Riley at the University of California-San Diego. These studies have shown the importance of knowledge for representing problems, consistent with results of research on problem solving in general physics. In addition, studies of learning and reasoning in electronics have provided information about interactions between qualitative causal understanding (how a system functions) and quantitative knowledge expressed in formulas (computational knowledge), and have shown that errors made by beginning students often are due to inadequate instruction in the qualitative properties of electronic systems. Analyses of methods for teaching the important qualitative properties have been undertaken, including work by Dedre Gentner and Allan Collins at Bolt, Beranek and Newman, that emphasizes utilization of analogy between systems with the same qualitative structure.

Another practical domain in which important cognitive analyses have been developed is medical diagnosis, where investigations have been contributed by Harry Pople and Jack Meyers at the University of Pittsburgh, by Edward Shortliffe and William Clancy at Stanford University, and by Paul Johnson and his colleagues at the University of Minnesota, among others. These studies have provided information about the organization of knowledge and reasoning processes involving very large bodies of information. Some general properties in this domain are shared with the conclusions based on research in physics, mathematics and electronics, including hierarchically organized concepts in the memory of experts and problem-solving strategies. Distinctive conclusions have been reached about the characteristics of competent performance, including: the organization of knowledge used in diagnosis according to multiple principles, taxonomic knowledge of disease categories and causal knowledge of bodily function and disease processes, and coordination of these different kinds of knowledge as a critical feature of successful diagnostic reasoning.

Systems of computer assisted instruction are being designed for training individuals to work with technical systems. One system, designed by John Seely Brown of Xerox Corporation and his colleages, is for training in electronic troubleshooting. This system enables a student to simulate the application of tests to obtain readings of relevant electrical properties of a device that is not functioning properly. The instructional system includes a sophisticated causal model of the device, enabling the student to understand the reasons for inferences that can be made from the readings. Another system called STEAMER is being designed by Albert Stevens and his colleagues at Bolt, Beranek and Newman Inc. STEAMER simulates the operation of a power plant, and will be used in training engineers. It also recognizes the importance of training students so that they can use causal principles about the system. The STEAMER system includes displays that show schematic representations of the power plant's internal structure, enabling students to observe effects of simulated changes in the system on properties such as internal pressure and rate of flow of substances that cannot be observed in real power plants. Thus, STEAMER illustrates the use of computer technology in training in which a simulation radically departs from the physical appearance of the real system, in order to provide crucial cognitive benefits that cannot be achieved in the real system or in a simulation that attempts to duplicate the superficial properties of the real system.

It is possible to study cognitive processes involved in use of technical systems either in terms of general cognitive principles or in terms highly specific to the technical system under investigation. Because of the rapid change in technology, highly specific work has a great danger of becoming obsolete before it can be used. Therefore, it is important to strive for general theory. The projects that we have described in this section illustrate investigations involving specific systems but with general cognitive principles being tested and developed as well. Studies at Xerox Corporation of text editing systems by Stuart Card, Tom Moran, and Allen Newell, and of instructions for operating copying machines by Lucy Suchman, also provide illustrations of investigations of specific technical systems that consider general principles.

II.A.3. Training in "Basic" Cognitive Skills. A long-standing issue in mathematics and science education has been the relative importance of teaching "basic" skills involving computational procedures and correct use of formulas vs. development of conceptual understanding. Traditionally much of the elementary curriculum has placed a major emphasis on skills. The curricular reforms of the 1960's challenged this emphasis and attempted to develop instructional programs that were more concerned with developing understanding of the structure of the subject matter disciplines. In reaction to this shift, the back-to-basics movement has redirected the focus back to skills. Today the importance of computational skills is again being challenged, especially in mathematics, where calculaters and computers are available that can perform all the calculations taught in school.

Results of recent research provide a basis for resolving the perennial conflict between skill and understanding. Recent findings have provided new information about the nature of skill and conceptual understanding showing that these cognitive components are mutually dependent. Rather than treating them as conflicting goals competing for scarce instructional resources, we can begin to design curricular materials that lead to skills that integrally include conceptual structures that provide understanding and make the skills more useful in problem solving situations.

Research on elementary arithmetic has shown that a substantial number of children learn incorrect procedures for arithmetic calculation. This phenomenon has been analyzed in detail and related to general theoretical principles by John Seely Brown and his colleagues at Xerox Corporation. Their analysis indicates that some children generate and use procedures that ought to be ruled out by basic concepts that should constrain arithmetic computation, apparently because they do not understand these concepts or their application in arithmetic procedures. Their analysis of processes generates flawed procedures that indicate knowledge of basic concepts that children lack and that should constrain arithmetic computation. Other research by Lauren Resnick at the University of Pittsburgh has explored forms of conceptual teaching for the correction of chldren's flawed knowledge of arithmetic procedures. This has led to an analysis of an integrated cognitive structure of arithmetic knowledge that relates basic principles of numerical representation of quantity related to the steps of correct calculation.

There also has been research showing that the structure of relationships between basic number facts can be used to facilitate the learning of basic arithmetic knowledge. Rather than teach number facts as a set of mere associations between numbers as is the case in the flash card approach that is commonly used, instruction that explicitly builds on relationships among sets of facts provides students with a framework for organizing their knowledge and significantly facilitates learning.

Teaching that involves the structure of relationships among individual facts also has been studied in the domain of physics by Jill Larkin of Carnegie-Mellon University. She developed instruction that showed how formulas are related by conceptual knowledge, and trained students to use this knowledge in deciding which formula could be applied in the solution of a problem. This instruction facilitated problem solving, providing further evidence that integration of skill and conceptual understanding is both possible and beneficial.

Skill in computer programming is beginning to take its place along with skill in performing mathematical operations and in using scientific formulas as a basic goal of education. There have been several studies in which the cognitive processes of computer programming have been studied, including work by Peter Polson at the University of Colorado and by Elliot Soloway at Yale University. Important properties of knowledge required for success in computer programming have been identified, including a differentiated hierarchical structure of schemata that is similar to the organization of knowledge underlying other cognitive skills that have been studied.

An important question about computer programming as an instructional goal is the extent to which training in computer programming leads to general improvement in problem solving and intellectual skills. This question has been addressed in research by Karen Sheingold, Roy Pea, Midian Kurland, and Jan Hawkins of the Bank Street College of Education, and by Elliot Soloway at Yale University. In the study by Sheingold and her colleagues, there was no more transfer from training in computer programming to other cognitive activities than is the case for training in other subject-matter skills. In Soloway's study, transfer occurred from programming to solution of word problems in algebra. Further research is clearly required to identify the ways in which training in programming provides generalizable skill, and the conditions in which such skills are acquired. In any case, there may be some especially beneficial side effects of instruction in computer programming; the research by Sheingold and her colleagues showed that there was more student interaction and discussion of intellectual problems in classrooms where computer programming was being taught.

In addition to studies of cognitive skill in specific subject domains, research also has been conducted on general factors in learning success. One important area that is under study involves skills that people use in approaching problems and regulating and monitoring their performance. In the course of learning, effective students show regulatory performances that include such activities as planning ahead and efficiently apportioning their cognitive resources and their time, predicting the correctness or outcome of their performance, and correctly deciding when or what they know or do not know in a particular learning situation. These forms of decision making are crucial aspects of efficient learning and problem solving because they enable an individual to use appropriate knowledge or to use appropriate procedures to obtain knowledge at the right time. Efficiency in performing them is particularly useful in facilitating transfer from learning and training situations to new situations. Research by developmental psychologists has indicated that these regulatory skills are predictors of success in the kind of problem-solving ability that produces learning, and that they are not well developed in individuals with difficulties in learning.

II.B. Participation and Effectiveness

II.B.1. Enlarging the Successful Student Group. An important condition for instructing a larger proportion of students successfully is to increase our understanding of the causes of their difficulty in learning. Major progress on this has occurred in recent research, especially in the identification of mistaken preconceptions that interfere with students' understanding of scientific concepts and principles.

There are profound educational implications of the findings that students begin their study of science and mathematics with implicit beliefs and tendencies to generalize their prior knowledge that are incompatible with the principles and procedures that they are supposed to learn. In current pedagogical thinking, there is considerable concern to avoid presenting incorrect information to students, but this is clearly not sufficient to prevent students from developing their own incorrect beliefs. Research findings have provided new understanding of why instruction can often provide students with ability to solve some problems correctly, but still leave them with an incomplete understanding of the subject. Frequently, the new vocabulary has been applied to their old concepts, and new formulas have been fitted into their previous knowledge structure. Remedial teaching generally consists of simply going over earlier materials again, as though students did not acquire the previous information completely; this ignores the fact that many students have formed procedures that are self-contained although incorrect. Thus, standard remedial teaching can be expected to be not only ineffective, but also to alienate students from the study of mathematics and science.

Research that has identified students' mistaken preconceptions has presented a common physical situation to students and used predictions that the students make as a basis for inferring the students' conceptions about the situation. An indirect method of assessment is required, since students frequently are unable to articulate their mental frameworks. Studies have been contributed by Michael McCloskey and his colleages at the Johns Hopkins University, by John Lochhead and John Clement at the University of Massachusetts, and by Audrey Champagne and Leopold Klopfer at the University of Pittsburgh. The findings indicate that even college students tend to think of basic phenomena such as motion and force in a way akin to the physical theories developed by classical philosophers 2000 years ago. Examples of misconceptions have been identified that are counter to the principles of modern physics, such as that stationary, rigid objects do not exert forces; that a constant unbalanced force is required to keep an object moving with a constant velocity; and that air pressure causes gravity.

Research also has shown that students' prior knowledge affects their learning in mathematics. Studies by John Clement at the University of Massachusetts and Kathleen Hart at the University of California-Los Angeles illustrate these effects. For example, after being taught procedures for solving problems involving proportions, children tend to solve those problems using whole number operations that the children generalized from their earlier instruction, rather than using the procedures that they had been taught for computation with proportions.

Research investigations are being conducted to explore new teaching methods that take students' prior conceptions and knowledge into account. Examples of these investigations include studies by James Minstrell at Mercer Island High School in Washington, by Dedre Gentner at Bolt, Beranek and Newman Inc., by Susan Carey and by Andrea diSessa at the Massachusetts Institute of Technology, and by Audrey Champagne and Leopold Klopfer at the University of Pittsburgh. These investigators are studying methods such as componential breakdown of situations in which students make incorrect judgments, analysis of limiting cases that make students' errors obvious, contrast of the learner's naive model with other more complete models, and discrimination training to make students cognizant of important distinctions that are neglected in their conceptualizations.

Along with findings that emphasize difficulties caused by students' prior knowledge and implicit beliefs, other findings have identified some important positive capabilities that have not been taken into account in the design of instruction. Many educators have concluded from Piaget's findings that children lack the conceptual structures needed to understand concepts of number, quantity, and causality until they are seven or eight years old, and that they lack important reasoning abilities such as the ability to reason hypothetically until they are in their mid-teens. Recent research by Rochel Gelman at the University of Pennsylvania, Thomas Trabasso at the University of Chicago, Ellen Markman at Stanford University, and others has shown that children have significant conceptual understanding of these concepts at much earlier ages than had been believed previously. Early understanding of these concepts is incomplete and largely implicit, but it is clearly not totally lacking, which means that instruction should be designed to capitalize on important conceptual building blocks that children have, rather than assuming that they have no cognitive basis for developing understanding of important abstract principles.

A major theme of the research that we have discussed in this section is the importance of understanding students' prior knowledge and conceptualizations to enable design of effective teaching of new skills and principles. In addition to new information about the kinds of prior knowledge and conceptualizations that students have, recent research has also provided improved methods for assessing the cognitive states that individual students are in prior to instruction. An example of these methods is in research by Robert Siegler of Carnegie-Mellon University, who has demonstrated that children's performance on specially designed sets of problems can be used to make sensitive diagnoses about the stages of understanding that they have reached regarding concepts such as the relationship of velocity, time, and distance travelled in linear motion. These studies also have identified stages of understanding that should be taken into account in designing instruction, showing that there can be intermediate states of partial understanding that should be achieved before there is an attempt to present a concept in its complete and complicated form.

The capability of educators to provide effective education in mathematics, science, and technology to an increased proportion of students will be enhanced also by increased understanding of processes of learning. Analyses of the cognitive processes involved in learning are in a relatively early stage, but some significant progress has been made. Contributions to this research problem have been made by John Anderson, by Robert Neches, and by David Neves at Carnegie-Mellon University, by Kurt VanLehn at Xerox Corporation, and by David Rumelhart and Donald Norman at the University of California-San Diego, among others. Important results of this work include analyses of how text information is transformed into cognitive procedures and how procedural knowledge in one domain transfers into new analogous procedures in another domain. Further results emphasize how difficult it is for learners to learn the conditions in which it is appropriate to apply the particular procedures or knowledge they have acquired. This reinforces conclusions from the study of problem solving that instruction could be made more effective if increased efforts were made to train students in the applicability conditions of procedures, rather than giving almost complete attention to the procedures themselves as often occurs in instruction at present.

Research on effective methods of teaching has also been conducted, including studies by Mary Budd Rowe at the University of Florida and by Allan Collins and Albert Stevens at Bolt, Beranek and Newman Inc. These studies have provided detailed analyses of the strategies that tutors use to formulate questions that probe and develop knowledge. Making explicit the strategies that Socratic tutors use should help more teachers achieve effectiveness in this style of learning, and generally provide insight into the interactions between students' existing knowledge and acquisition of new concepts and principles. In the more conventional classroom setting, instruction can be made markedly more effective if teachers provide more time for students to answer questions and pause briefly after questions are answered; the times involved are very brief, with increases of two seconds having substantial effects on a student's ability to process information before responding to questions. This shows that even quite simple features of classroom style and management can have substantial effects on learning experience. These results illustrate the interplay between general pedagogical issues and issues involving the specific teaching of mathematics, science, and technology. Just as these findings, obtained in research on teaching of science, contribute to general understanding of teaching practices, findings of research on teaching of other subjects provide important knowledge for use in the teaching of mathematics, science, and technology.

A major contribution to enlarging the group of successful students in mathematics, science, and technology can be made by increasing the participation of women and members of minority groups in instruction in these fields. Recent research has provided information about factors that contribute to choices of courses in mathematics and science, and the effects that these choices have on entry into scientific, mathematical, and technical careers. Studies on these problems include contributions by Alma Lantz at ESR Associates, by Lauress Wise at American Institutes of Research, by Jacqueline Eccles Parsons at the University of Michigan, by Elizabeth Fennema at the University of Wisconsin, and by Wayne Welch at the

University of Minnesota. Assembly of demographic information has shown that high school women's participation in mathematics courses has increased dramatically since 1960 and that women's participation in mathematics education generally is much better than is widely believed. Further, the research has shown that most of the sex difference in mathematics achievement is accounted for by differences in course participation.

Research on the determinants of course participation has confirmed some pre-existing ideas and disconfirmed others. Contrary to some usual beliefs, the extent to which a girl perceives mathematics to be sex-stereotyped and also her exposure to female role models seem to have little influence on enrollment decisions. Important determinants of participation in mathematics instruction include previous achievement in mathematics (not, however, an important factor in sex differences) and the individual's perception of the importance of mathematical knowledge. A girl's concept of women's roles in the world and of her own likely educational and occupational future does influence the usefulness that she sees in mathematics; this probably explains recent increases in enrollment. Prior achievement and ability level also are significant determinants of science enrollment. Interest in mathematics and a dimension characterized as "interest in things vs. interest in people" are important in differentiating science from non-science majors. As with mathematics, role models and perceived sex-stereotyping seem to be quite unimportant factors in determining participation in science education.

In the past decade, there has been considerable growth in the sophistication of evaluation methodologies. Now such complex questions can typically be addressed. In addition, some generalizations about intervention programs seem to be emerging. For example, lasting changes in attitudes and interests are not typically generated by passive media messages. These media materials, however, may be more effective when combined with face to face communication. Further, short "one shot" interventions do not appear to be highly effective while those spaced over a several-week period may be more promising.

II.B.2. Educational Use of New Technology. Research investigating cognitive and motivational factors in computer-based instructional systems has been contributed by several investigators. Contributions have been made by John Seely Brown and by Thomas Malone of Xerox Corporation, by Robert Davis and Sharon Dugdale at the University of Illinois, by Ira Goldstein of Hewlett-Packard Corporation, by Andrea diSessa at the Massachusetts Institute of Technology, by Allan Collins and by Albert Stevens at Bolt, Beranek and Newman Inc., by Audrey Champagne and Leopold Klopfer at the University of Pittsburgh, and others.

Among the concepts that have been investigated are use of computer-based systems for the development of more sophisticated problem-solving strategies by students, and the use of computational systems to simulate aspects of the environment that are unlikely to be observed in a real environment or that involve theoretically ideal conditions. One example is a system that shows graphically how a force applied to a moving object interacts with the existing motion of the object to produce a change in velocity. This requires students to revise a mistaken preconception that the final motion of an object can be completely controlled by the applied force, independent of its state of motion when the force is applied.

Research concerning motivational aspects of computer-based instruction has identified factors that contribute to the interest of instructional games. Important factors appear to include uncertainty of outcomes together with well-defined criteria for success in achieving goals. These are more significant motivational factors than are more superficial features such as use of music and similar superficial reinforcers when the student succeeds, at least in the preliminary studies that have been carried out.

II.B.3. Testing and Instruction. In recent years, there has been a series of major research programs that have provided assessments of the effectiveness and precision of testing for instruction and an analysis of theories on which the engineering of tests and test design have been based. Based upon former achievements in the psychology of individual differences and methods for the measurement of human behavior, testing has been developed to a substantial art and resulted in the development of major industries that supply testing instruments to education.

Also in recent years, the fundamental bases and properties of testing have been undergoing searching analysis and research examination. This has included examination of the ways in which tests are used in the educational process, and a reexamination of the theories of human behavior on which tests are based in the light of increasing knowledge of human cognition and the nature of skilled performance. At least two dimensions of this advance can be identified: (1) improved concepts and methods for diagnosis of individual differences in level of performance prior to instruction and for assessment of competence, knowledge, and skill that are acquired; and (2) the understanding and improvement of aptitudes for learning.

We have already discussed research advances that provide improved understanding of the nature of students' knowledge prior to instruction and the nature of cognitive skills that they acquire in instruction. As one application of this recent work, Herbert Ginsburg at the University of Rochester is drawing on contemporary research on children's mathematical thinking to develop a diagnostic test of calculation skill. The test focuses on strategies and processes underlying calculation: algorithms, systematic flaws, slips, and invented procedures. Properties of the test will be evaluated in relation to instructional purposes, particularly for remediation.

Regarding the nature of learning aptitudes, research has been contributed by Richard Snow and his colleagues at Stanford University, by Earl Hunt at the University of Washington, by Robert Sternberg at Yale University, and by Robert Glaser and his colleagues at the University of Pittsburgh, among others. Results of this research have contributed to development of models of the kind of performance that has been assessed on aptitude tests. Such performance of different types of mental abilities, e.g., language competence, the manipulation of abstract concepts and relationships, the ability to apply knowledge to the solution of problems and various perceptual and memorial capabilities. Recent models of cognitive performance have expressed detailed understanding of the nature of these abilities and the differences in performance of individuals with high and low measured levels of aptitude that can be considered in the development of new forms of diagnostic and achievement tests.

III. Research Needs and Opportunities

In this section we discuss questions for prospective research. We include topics for which research findings would have important implications for education in mathematics, science, and technology, and for which available scientific methods and concepts provide a strong basis for significant new investigations.

We begin with two general comments. First, the topics that are considered in Chapter II involve questions that merit further investigation to test the validity of our present conclusions and the applicability of the findings to additional topics in curriculum content and educational practice. Second, the conclusions that we have presented earlier require substantial efforts in applied research and development for their implications to be translated into concrete materials and methods for instruction.

In the remainder of this section, we identify important questions for prospective research involving new lines of inquiry that would be valuable, in our judgment, in addition to further development and application of the bodies of research that are discussed in Chapter II. We organize this discussion using the same general categories as were used in Chapter II.

III.A. Questions of Educational Content

III.A.1. Education for Effective Problem Solving, Reasoning, and Cognitive Skills. A central question regarding education's effect on students' general problem-solving and reasoning abilities is the question of transfer of knowledge and training. Scientific methods have been developed to the point that we can analyze the knowledge structures required for performance in problem tasks, and these methods can now be applied to enable individuals to use knowledge they have acquired in one domain to solve problems in another. Outstanding questions include the relative importance and instructability of general problem-solving methods and strategies, relative to methods and strategies that are tailored to the information and goals that arise in specific problem domains that occur in mathematics, science and technology. Results of research on this problem could provide valuable guidance for the development of educational programs in general problem-solving and thinking skills, which are receiving considerable attention, and which might be quite inefficient if they are being developed on the basis of implicit assumptions that turn out to be based on incomplete research findings.

A second research problem involves analysis of expert performance in mathematical, scientific, and technological domains. Much of this performance appears to involve processes that have become automatic for the individual. Research is needed to clarify the role of practice in the acquisition of these highly developed skills. A characteristic of highly automated skills is that they are relatively opaque and difficult to study scientifically. The nature of expert knowledge used in solving difficult problems (for the expert) is not well understood. Further, knowledge in the form that it is found in experts may not provide feasible instructional objectives for novices, who may need to observe performance in which the components and conditions are identified more explicitly than they are when an expert solves problems as examples for instruction. The relationship between knowledge as it occurs in experts and instructional methods needs to be examined thoroughly.

A third research problem related to these is a set of issues involving instruction in cognitive skills. Cognitive processes involved in the teaching of mathematics and science can be studied using the methods that now are used in studying problem solving and learning, and such studies would contribute needed information for the improvement of teaching and instruction. The design of text materials is based primarily on considerations of the organization of information in the subject matter. Organization of information for effective learning may differ from organization that provides the most elegant presentation of information in the subject matter. Studies of textbook content and structure in relation to the principles of cognitive skill acquisition that are being developed in current research would be valuable.

III.A.2. Education for Technology. Profound questions regarding our educational system are raised as our society gradually but inexorably becomes saturated with technology. Although craft technology preceded the rise of science and mathematics, the last half-century has finally seen technology become largely fueled by science. The result is the transformation of our environment to an artificial one -- that is, an environment where relations are predominantly mediated by technology.

The main implication for education of the saturation of society with technology is that understanding technology becomes a primary concern, along with understanding science and mathematics. For it is not true that understanding science and mathematics conveys an equal understanding of technology. To understand science is to know the hidden structure of the natural world, to see it as a domain of laws and predictability. To understand mathematics is to know the power of formal abstract symbolism to describe the scientific view of nature, and to see how the prediction, control, and explanation of nature arises from these symbolic descriptions. These prepare one for technology, but they do not provide an understanding of it and its use.

Technology is what happens in the long run when purposive processes exploit nature. In the short run, there occurs simply application -- the rational solving of problems. But in the long run there grows up a routinization of problem solving, in which the natural world gets permanently organized to permit purposes to be routinely attained. What results is a net of highly adapted artificial domains. The domains are law abiding and regular, but they are artificial in that they do not occur freely in nature. In Herbert Simon's felicitous phrase, the study of these domains can be called the artificial sciences.

Needless to say, very little is understood about what a student should learn about technology. We are only at the beginning edge of technological saturation. Our experience so far is that technologies are immensely diverse, each its own microworld of regularity. But in fact there are great underlying communalities, although many of them can only be pointed to at this point. Students should understand that technologies tend to consist of components with laws of combination that are highly reliable and understandable. We make them that way so that design and operation are easy. Design is a universal activity with technologies, and design as a cognitive activity has much in common for all technologies. Indeed, knowing something of design permits understanding of many features of artifacts. Processes of control are important and full control almost always implies an explicit control system alongside the basic technology. Questions of error, maintenance, and repair are central, as are specifications, testing, and certification, also costs and economies, and finally side effects and latent functions. All these concepts have no place in natural science and rise to prominence only when nature is organized to meet pervasive goals.

The current view of technology is of unbridled diversity, as we humans exploit natural structure in all conceivable ways. However, the continued and spectacular growth of computers along all dimensions of performance and cost is leading to their use for the control of all technology. This will have fundamental consequences for the shape of technology as it is perceived and felt by the citizenry. Many aspects of our society will come to be mediated by common interfaces with common capabilities and characteristics. These interfaces will continue to evolve, of course, but in ever-new forms they will still provide a major constancy in our lives, like roads and buildings, and even language. Learning about technology will have as a major component learning to live and work with computer interfaces, networks, and software tools.

Education for technology must become a concern of our educational process, taking its place alongside education in mathematics and science. Students must be introduced to the fundamental concepts of technologies, to see these both in their general form and in diverse ways so they come to understand their generality and specific applications. Research is needed to provide clear characterizations of the cognitive skills and knowledge needed for successful performance and understanding in technological domains, similar to those that are becoming available in mathematics and physics. In particular, there is a need for study of how people understand technological systems, including characteristics of their mental models, both to aid in design of training for use and maintenance of the systems and in design of the systems themselves to make them comprehensible, usable, and maintainable.

In fundamental ways, education for technology does not differ in kind from education for science. The content is different, as indeed is the content of one science from another -- e.g., physics from chemistry or astronomy. But in other ways, the conditions are quite unique. First, we are at a very early stage in our understanding of technology as a general category. Thus the fundamental concepts are not as clear as are those of science. But even more, society is in a developing state with respect to technology itself, not just with respect to our understanding of it for intellectual and educational purposes. Thus the actual state of technology a decade hence will be quite different than its state now and new principles may well be emerging then.

The ascendency of the computer as a universal control system provides a not too far-fetched example. With such a movement could arise the homogenization of technology, so that an immense amount of intercommunicability would be possible over all uses. Such constancies would have the utmost significance for the general use of technology by the entire population, and would rate a fundamental place in the characterization of technology. (Lest anyone still think this is too farfetched, consider the development of the physical bit (i.e., the two-state device) as the common coin for all digital technology. In the

40s and 50s machines were built with triadic logic and other non-binary logics. All that has disappeared, presumably permanently.) As technology in the school (and the rest of one's life) becomes ubiquitous, there will be no need to have a special computer laboratory with artificial problems in order to gain experience. The uses of the computer for many educational functions will provide "real-life" examples of technology in action. The correspondence of the means-ends structure of technologies to an individual's own means-ends structure of thinking and problem solving will require research to see whether persons' views of their own rationality constitute a "naive rationality" analogous to naive physics that is more an impediment than an aid in understanding the rational structure of technologies.

We need to know more about the cognitive skills and knowledge that are required for intellectual tasks in the nonacademic settings spawned by technological advances. Methods of cognitive analysis can be applied to identify knowledge structures that are needed for successful performance in technical occupations, and for successful use and understanding of technology in our lives.

The idea that technology joins mathematics and science as a triumvurate of basic domains seems to respond to important changes in our society. But some cautions are in order. One comes from the existing state of nonintegration of mathematics and science education. To a large extent, each goes its own way. If the result of adding technology is to create three separate educational domains, each following its own course, it might be better to forego the whole enterprise and simply muddle along. One possibility for hope is that the use of technology throughout the curriculum could perforce produce integration at a more rapid rate than the educational pigeon holes can promote its decay.

III.A.3. Training in Cognitive Skills. A major program of applied research and development is called for to design instructional methods and materials that exploit research results showing that conceptual understanding and formal skill are integrally related. In addition, the frequent occurrence of flawed procedures that are acquired by students raises the important research question of how incorrect procedural knowledge is learned. Investigation of this question will provide important information about fundamental processes of learning as well as indicating ways in which instruction can be improved to prevent the occurrence of incorrect learning.

Improvements in learning can come about by the design of a program of research and development that focuses on the learning skills that enable individuals to profit from instruction and further experience. The demonstrated importance of regulatory activities as a factor in learning success provides a basis for further investigation to analyze those skills in detail and determine whether they can be increased through instruction for general improvements in learning ability.

III.B. Participation and Effectiveness

III.B.1. Enlarging the Successful Student Group. We now understand that children have preconceptions about topics in science and mathematics that interfere with their understanding of concepts and principles. Research that investigates processes of changing students' mistaken preconceptions is in an early stage, and can be conducted productively with available methods and concepts. We also know very little about the causes of children's conceptualizations. It seems reasonable to conjecture that many of them arise as inferences from ordinary experience -- for example, to keep an object moving we must continually apply a force to overcome friction and gravity; perhaps this produces the pre-Newtonian inference that bodies in motion tend not to remain in motion. However, this reasonable conjecture should be examined and tested. A more subtle hypothesis is that the conceptualizations that children develop are a result of their effort to understand the phenomena that they experience, and have important explanatory functions in children's cognitive structures. If this is the case, the educational remedy for mistaken preconceptions will be much more complex than if the preconceptions are simply inductive generalizations. Rather than simply being faced with phenomena that contradict their preconceptions, children will have to acquire new explanatory concepts and relate them to the phenomena that they have understood previously in terms of a different set of concepts.

A closely related issue is whether understanding of modern concepts of science and mathematics requires proceeding through a series of stages involving incomplete and partially incorrect concepts, or whether an appropriately redesigned set of experiences would allow children to avoid the mistaken ideas that typically occur.

An important question for enlarging the group of individuals who understand scientific and technological principles involves the extent to which these principles can be acquired through informal experience that occurs outside of the academic setting. Scientific and technical information is available in our society in a great variety of settings, including museums and television. Systematic investigation of the processes of learning in these settings could provide important guidance for programs designed to disseminate information to the public in a broad way.

Cognitive learning theory is ripe for expansion into a theory that can speak to motivational issues such as those raised by computer games, by sex differences in math and science enrollment, and by public distaste for "school math" and "school science" concurrent with public interest as evidenced by the popularity of science magazines, television programs dealing with science, and home computers. Work is needed on the extent to which extremely high levels of motivation (e.g., from electronic games) help or hinder different qualitative types of learning, such as conceptual learning or practice.

Regarding participation of women and members of minority groups in mathematical, scientific, and technical education, simple factual information about some aspects of participation is still needed. In particular, information about the math and science participation of the members of various minority groups is needed. This information should be broken down by the relevant ethnic groups that can be expected to differ and by sex within them.

Research is needed to determine how much of the large effect of prior achievement is due to the intrinsic difficulty of continuing after poor mastery of prior work and how much is due to the selection, tracking, and counseling practices of schools.

Methodologically sophisticated measurement of the importance of factors other than achievement is needed, especially for populations other than the "general" population, and especially for factors such as interest, liking, confidence, and perceived utility that are to be the focus of intervention efforts. There is a need to determine the common and independent effects of these factors and prior achievement or ability.

There is a great need for research into the mathematical and scientific concepts and skills that are actually needed in a variety of life roles — whether as a common citizen, a business person, or as a scientific and technical professional. Students, teachers, and the general public have little knowledge of this and the perceived need for mathematical and especially scientific education is presumably reduced by that lack of knowledge.

Research into the early development of scientific interests is needed. Interest patterns seem to be a major determinant of participation is science, but little is known about their origin and development. Cognitive explanations of interest should be explored. It is possible that interest depends upon appropriate prior knowledge and experience. For example, females seem to have much less informal science-related experience with toys and hobbies in childhood. The possibility that the examples in science textbooks are biased toward majority male interests should be explored, as should effects of television programs such as "Cosmos" and "3-2-1-Contact," and other popular science media exposure upon science interest. Sophisticated evaluation of intervention programs designed to increase science participation is needed. To date there has not been a close correspondence between interventions designed to encourage participation and the research on significant factors involved in participation. For example, many of the interventions have focused on the presentation of role models, while the research has suggested the importance of achievement.

Despite the great increase in girls' enrollment in advanced high school mathematics, there are still great variations from school to school in the level of girls' participation. Research is needed to determine what characteristics of schools seem to promote high levels of math and science participation for girls, minority students, and all students, other than obvious factors such as high ability levels of the incoming students or the high socio-economic status of the community.

Since there has been, and presumably will continue to be, some emphasis on interventions designed to encourage science participation, these interventions need to be based on existing research and to be thoroughly evaluated. These evaluations, while initially expensive, are the only way to ensure cost-efficient programs in the long run. Several methodological developments are needed: it is necessary to have adequate experimental designs and measuring instruments to assess the effects of an intervention. Further, assessment of short term outcomes of global measures are not adequate. Long-term followup of specific components is needed. For example, many of the interventions combine many elements -- academic enrichment, "hands-on" manipulation, and vocational information. It is imperative to determine the relative and/or combined effectiveness of these components. It is also necessary to determine whether there are differences in effectiveness for various individuals, subgroups, such as women and minorities, and whether these differences may be specific to certain ages, fields, or background characteristics of the learner.

III.B.2. Educational Use of New Technology. Technology develops best when scientists with new theories are kept involved in the exploitation of their ideas. For this reason, an important form of research is the development of exemplary prototype instructional computer systems, both to lead the private sector and as research vehicles for more targeted basic research on learning and instruction. Some of the prototypes that seem most likely to be important are intelligent tutors that can help improve the effectiveness of the current teacher corps and, in fact, could provide instruction to both children and their teachers.

Prototypical systems also are needed to exploit the computer's capability to simulate and explicate mathematical and scientific principles. Systems of this general kind have been developed for topics in elementary mathematics and physics, but richer versions dealing in greater depth or with more complex subjects are now needed. More important, these systems need to be exploited as cognitive research vehicles. Prototypes are needed also to provide examples of use of environments for instruction in programming, and systems that provide diagnosis and assessment of students' specific knowledge and more general levels of capability in mathematical and scientific domains.

Experimental schools, in which the use of these tools in heavily saturated modes is possible, would substantially aid cognitive research on mathematics and science learning. Some systems should also be placed in nonschool settings (settings open to the public, such as libraries or museums) to facilitate research on updating the technological and scientific knowledge of the general adult populace.

A general issue that should be addressed in the context of the above systems is the extent to which intensive environments can be developed in which students are immersed in using science and mathematics. Do such environments result in substantially better learning? To what extent do integrated programs of mathematics, science, and technological content facilitate learning?

Computer-rich classrooms allow new styles of learning. Of particular importance are learning activities involving pairs or small groups of students, peer tutoring, collaboration/competition, etc. Observational and other research is needed in order to have a better description of processes and outcomes in such environments.

III.B.3. Testing and Instruction. Work is needed on a cognitive psychometrics, a science of measuring the level of skill attainment in cognitive domains. With such assessment capability, work should proceed on the evaluation of novel programs of instruction, including use of programming environments. Particular attention should be paid to the extent to which skills learned in these domains transfer to other technological areas and conditions under which such transfer occurs.

Research is needed on aptitude differences and ways of tailoring intelligent instructional interactions to aptitude differences. Microtheory is well on its way that provides a basis for diagnosing deficiencies in cognitive procedures by specifying in detail the components of procedures that give errors in performance. There is a significant need for theoretical development for assessment of students' conceptual understanding related to their procedural knowledge, including their knowledge for representing problems and of principles related to general problem-solving methods. Theories dealing with more general aptitudes (e.g., reading facility, spatial/visualization skills) need much more work but have high potential longterm payoff. Some of this research should be specifically directed at differences that relate to equality of access by both sexes and by different races and cultures to math and science education.

IV. Structures for Application and Support

In this final section we comment on some conditions that we consider important for the continued development and use of scientific knowledge about cognitive and behavioral processes relevant to education in mathematics, science, and technology.

We are particularly concerned with development of conditions that will increase the accessibility of research findings within the various communities that provide instructional materials and teaching services. The relationship between cognitive science and the educational community is not nearly as close as the relationship between physical science and engineering. To a large extent, the greater distance between science and practice in education results from the recency of development of many of the basic scientific ideas and methods. But current understanding of human cognition is at a point where it is important to develop conditions that enable the use of scientific results as easily and quickly as the usefulness of the results warrant.

A necessary condition for the development of new materials that take account of research findings in cognitive science is collaboration in research and development between cognitive researchers, specialists in the subject matter domains of mathematics, science, and technology, and educators. This is needed to ensure that instructional development will be informed by a deep understanding of the requirements of classroom instruction and of the conceptual structure of the disciplines to be taught, as well as the best available knowledge of learning and thinking processes. In the past, the programs of research and development in science education at the National Science Foundation have facilitated this kind of collaboration in valuable ways.

A critical dimension of efforts to facilitate application of research results is the training and retraining of teachers. One key difference between today's educational research climate and that of 20 years ago is a growing recognition that the teacher should be considered as a serious professional who can become involved in curriculum construction and the interpretation of research. Teachers should be collaborators in doing research as well. Programs should be considered that would enable teachers to spend substantial amounts of time regularly in collaborative research with other teachers and with cognitive and behavioral scientists. This would enable teachers to develop greater confidence and competence in developing curriculum for their own classrooms, and also to begin to understand and appreciate contributions that recent research in cognitive science can make to their teaching. Inclusion of teachers as collaborators in research would also benefit the research enterprise by providing continuing information about the context in which research findings will be applied.

Use of research findings also depends very strongly on the process of teacher training, and programs could be considered that would provide incentives for schools of education to develop innovative ways to include findings of recent research in their courses and in-service training institutes.

As with any science, research relevant to education in mathematics, science, and technology is a cumulative process that requires continuity of support if it is to maintain a productive level of contributions. The quality of American education in mathematics, science, and technology stands to benefit from maintenance of a stable source of support for scientific research on cognitive and behavioral processes. At the present time, there is scientific knowledge available that could be used for improvement of educational materials and methods, and an increased effort in basic research would provide further results of considerable value. We judge that an increased level of support would be beneficial for this work, and estimate that increased funding at a rate of as much as 20% per year could be used productively for major improvements in a citizenry prepared with the knowledge and skill required for personal growth and social contribution required in modern scientific, technological societies.