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ABSTRACT

Forty-five educators, mathematicians, scientists, cognitive scientists, and curriculum and technology experts met during January 16-19, 1986, in an attempt to synthesize the current state of knowledge about science education and to recommend actions designed to strengthen the field. This report describes the themes that emerged from the discussions at the conference. Four major recommendations were made by the group that were intended to encourage the development of an integrated research base in education. The recommendations are to: (1) establish centers for collaboration in science and mathematics education; (2) expand opportunities for sharing information and building communication networks; (3) increase the fundamental understanding of science learning and instruction; and (4) strengthen the response of research in science education to real instructional needs. The bibliography includes a selected list of papers written by the participants and a set of review articles. (TW)

Establishing a Research Base for Science Education: Challenges, Trends, and Recommendations

Report of a national conference held January 16-19, 1986

Sponsored by: *Lawrence Hall of Science and the*
Graduate School of Education
University of California, Berkeley

Report by: *Marcia C. Linn*

Executive Committee: *Marjorie Gardner*
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Executive Summary

On January 16-19, 1986, forty-five mathematicians, scientists, cognitive scientists, mathematics and science educators, and curriculum and technology experts convened at Berkeley for a planning conference on research and science education. The conference was sponsored by the Lawrence Hall of Science and the Graduate School of Education at the University of California at Berkeley, and funded by a grant from the National Science Foundation. The conference, based on the recognition that both current experimentation and long-term goals in high quality science education must be rooted in a strong research base, had the following objectives:

- *to assess the current state of knowledge relevant to education in mathematics, science, and technology, and to make recommendations for disseminating results already in hand to increase educational effectiveness,*
- *to evaluate the potential benefits of activities within the current scope of research funding agencies (including NSF), by assessing how well they contribute to a research foundation of knowledge and principles that can beneficially influence the practice of science and mathematics education,*
- *to identify opportunities for major new advances in selected research areas which might be achieved with the appropriate allocation of resources, and*
- *to recommend priority areas for research and effective research methodologies directed toward establishing a theoretical framework for science and mathematics education.*

Participants at the conference came from a broad range of disciplines, bringing with them many different perspectives. Many of the participants had not met each other and would seem to have only a small degree of overlap in their work. They came, however, with a shared commitment to the highest quality of science and mathematics education. They came ready to experiment with the idea of science and mathematics education. They came willing to experiment with the idea of multidisciplinary collaborative work, and interested in the possibility of establishing a unified view regarding important areas of research for funding and development. The conference was an experiment, an attempt to build a collaborative community of disciplinary experts working on serious educational issues. To some degree, its results will be best measured five years hence -- if a collaborative community has begun to cohere and function effectively. But there certainly were short-term signs of significant progress. There was a high degree of energy and exchange at the conference, some controversy, but also many signs of emerging collaborations among the members of different disciplines. It will be essential to nurture such interdisciplinary work, and to help implement the recommendations that emerged from the discussions. Those recommendations include:

- *Establishing centers for research collaboration in science and mathematics education.*
- *Expanding opportunities for sharing information among constituencies involved in science and mathematics education.*

- *Increasing research on fundamental understandings of learning and instruction in science and mathematics.*

- *Responding effectively to instructional needs.*

The conference report expands on these recommendations. It provides an extensive description of the current state of research and practice, a discussion of the participants' views as to where we should be heading, and a discussion of promising methodologies, ideas for making progress, and suggestions for implementation.

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Establishing a Research Base for Science Education: Challenges, Trends, and Recommendations

Report of a national conference held January 16-19, 1986

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1 Introduction

We have put people on the moon, synthesized insulin, designed supercomputers, and harnessed energy. But we have not succeeded in building a nation of informed citizens confident of making reasoned decisions about the myriad scientific issues that affect our lives.

The unprecedented pace of scientific and technological innovation since the middle of the century has made insistent demands on science education. The quality of the science training received from the pre-school years on affects how well citizens understand their increasingly complex world and how effectively they cope with change. The explosion of new technologies and new information has challenged science educators to revise traditional approaches and set new priorities. This challenge has not yet been satisfactorily met. We have, to be sure, produced brilliant researchers who have advanced the frontiers of knowledge. We have put people on the moon, synthesized insulin, designed supercomputers, and harnessed the energy. But we have not succeeded in building a nation of informed citizens confident of making reasoned decisions about the myriad scientific issues that affect our lives. Democracy demands no less than this level of preparation. To sustain scientific momentum and to extend scientific literacy to all citizens, we need effective, responsive science teaching and an effective, responsive research enterprise for science education. Recent advances in understanding how students solve problems in the science disciplines have given researchers hope that new tools can be developed to improve the quality of science education in the United States.The needs of our citizens demand a serious, concerted, systematic response. We submit this report in this spirit.

Background

Research in science education today has been invigorated by the collaboration of a broad spectrum of researchers across traditional disciplinary lines. To nurture this new development, the Lawrence Hall of Science and the School of Education at the University of California, Berkeley, with support from the National Science Foundation, assembled leaders in science education research for a conference and asked them to:

- *synthesize the current state of knowledge about science education.*
- *recommend actions to strengthen the science.*

This report describes the themes that emerged from the discussions at the conference and makes four recommendations intended to encourage the development of an integrated research base in science education and to infuse science teaching with ideas and techniques informed by research and dedicated to meeting the challenge of change in a technological world.

Research plays a key role in improving science education, just as it advances our knowledge in the traditional scientific disciplines. Recent research into the cognitive processes involved in teaching and learning science has made it possible to integrate research, resource development, and instruction more closely.

This report seeks to encourage researchers and educators alike to combine their efforts to add to a systematic, comprehensive research base for science education.

The new thrust in science education research incorporates the contributions of cognitive scientists, specialists in the traditional science disciplines, science educators, mathematics educators, linguists, psychologists, curriculum developers, philosophers, sociologists, historians of science, anthropologists, artificial intelligence experts, pre-college teachers, and other educators. This report seeks to encourage researchers and educators alike to combine their efforts to add to a systematic, comprehensive research base for science education.

Throughout this report, science is broadly construed to include biology chemistry, physics, geology, mathematics, and technology--the sciences offered in the pre-college curriculum.

Problems

Several important studies document the serious problems in science education today. ***A Nation at Risk***, a report of the National Commission on Excellence in Education, found that "the average graduate of our schools and colleges today is not as well educated as the average graduate of 25 or 35 years ago."

Educating Americans for the 21st Century, a report to the National Science Board, revealed that the instruction students receive in science does not prepare them to cope with the problems they will face and argued that students need to learn the "new basics" - the thinking skills required for choosing among new medical treatments, for example, or pursuing careers in technologically rich environments, or investing wisely.

The research briefing panel on Information technology in pre-college education of the National Academy of Sciences further documented the lack of an appropriate science curriculum, reporting that science and mathematics classes fail to integrate low-level skills and high-level understanding. As a result, what is studied is neither understood nor remembered.

Rapid changes in society during the past decade make change in the educational enterprise particularly necessary. We have become an "information society". Available information doubles every 2.5 years. Skill in locating and utilizing information to solve problems has become far more critical than skill in memorizing information. We have become a "technological society". Technological tools now permeate most vocational and leisure activities. Yet, during the same period:

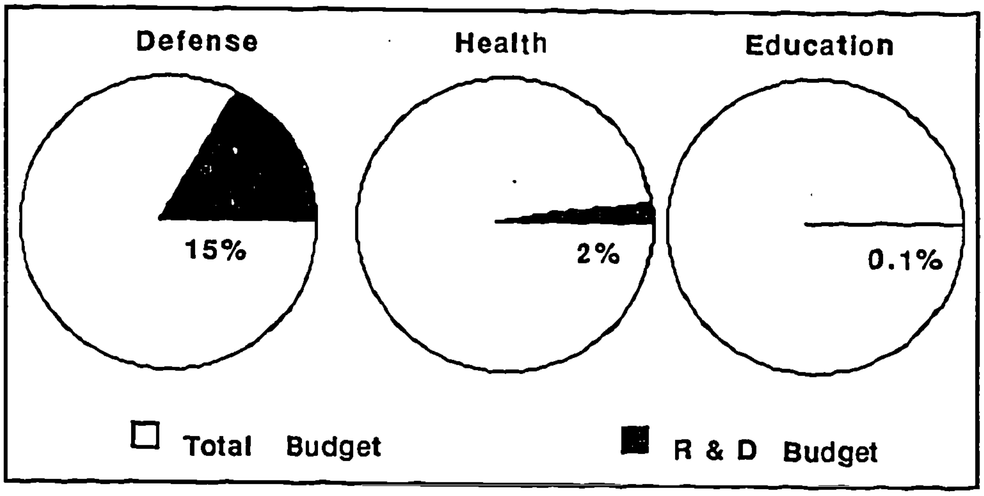
- *Enrollment in college preparatory science courses has declined. Only about 15% of high school students study physics today. While there is more to learn, fewer people are learning from available courses.*
- *A smaller number of pre-college teachers are qualified to teach mathematics and science*
- *Student achievement in science and mathematics has declined and lags relative to other industrialized countries.*

- *Technological advances have not been effectively incorporated into educational programs. In the last seven years, schools have purchased 1.2 million microcomputers but often lack software, curricula, or teachers trained to use them. Advanced technologies become economically feasible for schools before curricular materials appropriate for them can be developed and tested.*

Obstacles

Many serious obstacles stand in the way of improving science education.

Federal support for education research is far too small. Total expenditures for educational research and development comprise less than one-tenth of one percent of the education budget. Twenty times as much of the health budget is allocated to health research and development, and 150 times as much of the defense budget is allocated to defense research and development. The chart below illustrates this astonishing situation.



Furthermore, funding has been unpredictable from year to year. Sustained funding is required to build the infrastructure to coalesce the diverse groups contributing to the new thrust in science education research. Talented students cannot count on continued support and therefore steer away from the field. Stable and widespread funding is essential for post-doctoral scholars,in particular, because they generally must master at least two disciplines--physics and cognitive theory, for example.

Finally, the status and remuneration of teachers in this country poses a fundamental obstacle to reform. As long as teachers are poorly paid, as long as isolation and heavy workloads are the norm, as long as teaching lacks respect, as long as teacher education remains outdated, as long as high schools are embattled, as long as parents undervalue education, change will be extremely difficult.

We do not discuss these critical underlying issues here. Instead, it should be clearly understood that funding must be increased and the status of teachers improved in order for our recommendations for science education to have the maximum salutary impact.

The Science Education Enterprise

A small but growing group of researchers, spurred by common interests in such fundamental questions as how students learn, has begun examining these questions from an interdisciplinary perspective. From the collaboration of this fledgling interdisciplinary community has come a new thrust in science education research.

Researchers involved in science education usually engage in independent programs within a single discipline. Recent advances in fundamental understanding of learning and cognition as well as recent technological advances inform science education. As a result, a small but growing group of researchers, spurred by common interests in such fundamental questions as how students learn, has begun examining these questions from an interdisciplinary perspective.

From the collaboration of this fledgling interdisciplinary community has come a new thrust in science education research that has produced important advances in knowledge and has heralded the beginnings of a more coherent view of the educational enterprise generally.

Researchers contributing to the new thrust in science education research have formed groups like Psychology and Mathematics Education (PME) and have become vocal subgroups in the Cognitive Science Society, the American Educational Research Association and the American Psychological Association.

New journals that cross disciplinary boundaries and encourage collaboration - like ***Cognition and Instruction, The Journal of Mathematical Behavior,*** and ***For the Learning of Mathematics*** - have begun to appear, and established journals - such as the ***Review of Educational Research, the Journal of Research in Science Teaching, the Journal for Research in Mathematics Education, the Educational Studies in Mathematics, the European Journal of Science Education, Cognitive Science and the Journal of Educational Psychology*** - now include articles reflecting this trend.

2

The New Thrust in Science Education Research

Several research themes have emerged over the past decade as a result of interdisciplinary work. These form the basis of recommendations for future work. They include:

- *a growing consensus about the nature of the learner,*
- *a new view of the curriculum,*
- *a new view of teaching, and*
- *exploiting the new technologies.*

These themes were the focus of discussion at the conference and are highlighted below.

A Growing Consensus about the Nature of the Learner

Using the seminal studies of Jean Piaget and others as a point of departure, science education researchers working together have begun to expand our fundamental understanding of how students learn. Based on a growing body of new research, a consensus about the nature of the learner is emerging.

Learners actively construct an individual worldview based upon personal observation and experience. They respond to formal instruction in terms of this preexisting intuitive perspective.

There is widespread agreement that learners actively construct an individual worldview based upon personal observation and experience and that they respond to formal instruction in terms of this preexisting intuitive perspective. Research has also revealed that learners construct a sense of themselves which guides their learning behavior. Furthermore, the experiences and observations of learners in different population and cultural groups may lead to distinct worldviews that manifest themselves in diverse responses to science instruction.

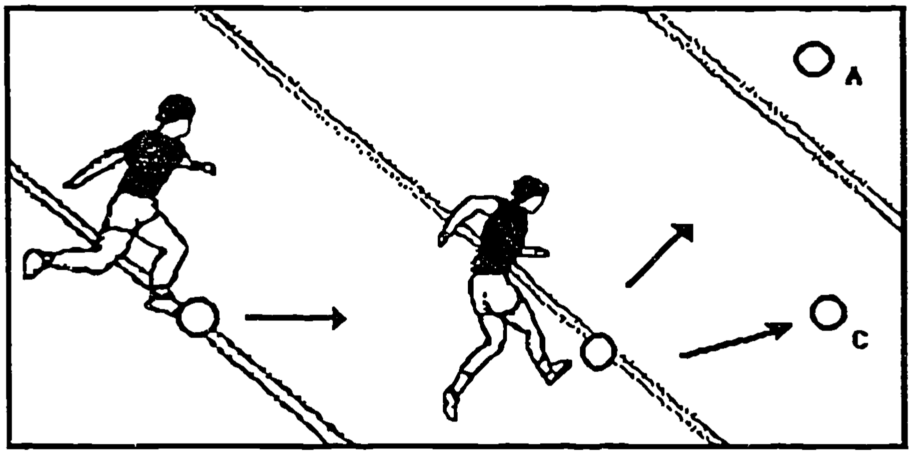
This growing consensus about the nature of the learner has in turn increased our awareness of the complex nature of education. Students must not only gain access to new information, they must also integrate this information with naive, perhaps erroneous intuitive ideas. In addition, their perception of themselves, based on previous experiences, affects their success at integrating new information.

Constructing a View of the Natural World, Mathematics, and Technology

Remarkably, learners often agree among themselves about how the world works, but their views often vary from those of trained scientists.

Jean Piaget's classic studies of children's conceptions of the world have influenced educators to respect the learner as one who actively constructs a coherent worldview and who seeks persistently to integrate formal and informal learning experiences. Remarkably, learners often agree among themselves about how the world works, but their views often vary from those of trained scientists.

It is not surprising that learners construct ideas about the natural world, mathematics, and technology that differ from those of scientists. Observation of natural phenomena provides meager clues about the mechanisms that govern them. For example, observing motion in a friction-filled universe leads citizens to reach many of the same conclusions reached by Aristotle. Since objects usually move in the direction in which they are pushed, observers tend to ignore the role of momentum when predicting what will happen when a soccer ball kicked towards the goal is then kicked towards the sidelines, as shown in the illustration below. Many will predict that the ball will go in the direction it was last kicked, or to point A, while others will realize that it will go somewhere between A and C, depending on the force of each kick.



Furthermore, students who have studied physics make observations about force and motion that are inconsistent with the principles they have been taught. Teaching correct principles is not sufficient. Young children have deeply ingrained ideas about causality and quantity that influence what they learn. Teaching correct scientific ideas requires restructuring the concepts that children have, rather than simply supplying correct concepts.

Observations of technological advances can also lead to intuitive ideas that differ from those of experts. For example, the superficial similarities of microcomputers and typewriters lead young students to think of microcomputers as electronic typewriters. These students have considerable difficulty understanding the nature of a stored program because they do not realize that computers have the capacity to remember.

The Central Role of Content

Learners build conceptual frameworks that are complex, highly organized, and strongly tied to specific subject matter.

The new consensus about the learner reflected in recent research extends the constructivist view of Piaget by recognizing that learners build conceptual frameworks that are complex, highly organized, and strongly tied to specific subject matter.

Piaget demonstrated that young children have unique, predictable ideas about scientific phenomena; he emphasized the uniformly experience-based nature of children's early ideas. In recent years, researchers have studied the mechanisms students invoke and the frameworks or models they construct to explain events in specific disciplines.

Detailed study of the models that students construct to explain energy, or motion, or genetics, or gravity, or subtraction reveals that these models involve broad concepts that organize ideas across a subject matter domain. Students acquire principles to encompass phenomena that they believe are related. For example, students frequently develop a single thermal concept to encompass both heat and temperature. They expect a large beaker of boiling water to have as much "heat" as a small glass of boiling water. They use this concept when reasoning about insulation and heat transfer.

The new consensus about the learner draws attention to the ideas that students form intuitively and to the explanations they use to defend their ideas in the face of new information. This consensus begins to explain how students' intuitions originate and are shaped by what they learn in the classroom. Promising research on this question combines computer models of the process by which learners construct new ideas and detailed studies of individual learners.

The new consensus about the learner respects the complexity of students' conceptual frameworks and illustrates the powerful thinking tools they use to form their ideas. The Piagetian view stressed the role of formal operations or general logical rules in students' reasoning. Recent research suggests that students' intuitive ideas about a discipline overshadow the potential influence of general reasoning patterns, such as those characterizing the scientific method or critical thinking. These findings emphasize the importance of identifying and articulating the learner's ideas and thinking skills within a subject matter domain as a basis for designing instruction.

Students constantly interpret new information based on their particular worldview. Their misconceptions, therefore, do not arise merely from failure to absorb information but rather from erroneous interpretation based on intuitive perceptions that must be overcome.

At times, the Piagetian perspective has been used to emphasize the perceived limitations of the learner based on developmental constraints in order to suggest what not to teach. The new consensus about the learner places greater importance on what the student already knows and what the student can learn. One major implication for teaching strategy which emerges from our better understanding of the learner is that it is inappropriate to assume that students simply absorb information. Rather it appears that students constantly interpret new information based on their particular worldview. Their misconceptions, therefore, do not arise merely from failure to absorb information but rather from erroneous interpretation based on intuitive perceptions that must be overcome.

Cognitive scientists and specialists in the traditional science disciplines are starting to share ideas about how students solve problems. Studies in physics, for example, reveal that college students in first year physics classes solve mechanics problems by substituting the information they are given into the formulas they know and then manipulating the formulas algebraically, making substitutions until they get the required answers. In contrast, college physics teachers tend to transform the problems until they correspond to some general laws of physics, such as conservation of energy, and then apply the formulas in a straightforward manner. Teachers, thus, systematically represent their physics knowledge in terms of the laws of physics, incorporate the problems presented into this representation, and quickly find solutions, while their students rely upon means-ends problem solving. Researchers have identified instructional procedures that teach students to construct an understanding of the laws of physics that improves their problem solving.

Through research such as the studies cited in the references, a more coherent view of the learner is emerging; however, much additional research is needed to augment our understanding.

Constructing a World View

The study of conceptual change is deeply rooted in educational history, was a concern of Plato's, and was discussed eloquently by Rousseau in ***Emile***. How and why learners construct and change their scientific worldview is a fundamental question for historians of science, philosophers of science, cognitive scientists, and science educators alike. Recently, researchers in these fields and others have begun combining their different perspectives to explore this issue. Since learners generate both powerful and obfuscating ideas, the challenge for researchers is to learn how to foster more powerful ideas.

The multidisciplinary approach has not only strengthened these research efforts, it has also enriched the disciplines involved. For example, comparing how children construct separate ideas about heat and temperature to how these ideas have emerged historically has benefitted those in science education as well as those in the history of science.

Researchers in many fields, including philosophy, history of science, psychology, education and sociology, share the perspective that reasoners resist changing their ideas. Empirical studies of how learners incorporate seeming contradictions into their scientific views coincide with philosophers' descriptions of how slowly scientific ideas change. Theoretical and empirical studies in psychology and sociology of how learners and institutions resist change have parallels in work on resistance to new ideas in science. A growing body of research, therefore, pinpoints the potential difficulties of changing students' ideas, indicates how these coincide with the new consensus about the learner, and has implications for instruction.

Other Ways to Acquire Knowledge

Not all learning requires restructuring of ideas. Some important new work from a behaviorist perspective has increased our understanding of the conditions that predispose learners to accept new information. Research focusing on building a coherent structure of new propositions, rather than integrating new information with intuitive ideas, has lead to formal models of knowledge required for tasks such as arithmetic computation and geometry proof generation. Those engaged in this research have used these models to generate powerful computer learning environments that teach students subjects like logic, geometry, and computer programming.

Serving the Needs of All Students

Different cultural groups have distinct world views, reflecting their different formal and informal learning experiences. Instruction must respond to this diversity.

Because learners build new understanding upon their previously formed ideas, the different perspectives of cultural and population groups require special attention. Furthermore, rapid change in minority group distribution increases the need for effective education nationwide. Empirical research reveals that different cultural groups have distinct world views, reflecting their different formal and informal learning experiences. Instruction must respond to this diversity. For example, some cultural groups stress non-mechanistic explanations for scientific phenomenon. Curricula that emphasize the mechanisms governing natural phenomena directly contradict this view and will have differential success depending on the backgrounds of the students. Other groups emphasize the interdependence of science and society. Curricula that neglects this interdependence may be ignored by some students. To achieve educational excellence, we need instructors who support and encourage all learners. Instructors need skills and information in order to recognize, respect, and respond to the perspectives of women, hispanics, blacks, and other cultural and population groups. We need curricula that incorporate what we know about conceptual change to teach all students the fundamental ideas of science rather than serving some while ignoring the prior learning of others.

Differential participation in or access to informal learning experiences contribute to the different worldviews students bring to science learning environments. Girls are less likely than boys to participate in science-related out-of-school activities, for example. Learners from lower socioeconomic status groups are less likely to have science-related informal learning experiences. Population groups such as women and those from the lower socioeconomic statuses are less likely to gain access to technology and less likely to be exposed to exemplary programs when they do have technological access. Such differences in experience have implications for performance in formal education settings, because students lacking informal learning opportunities may have less powerful or appropriate intuitive ideas about the curriculum. By encouraging and providing informal science experiences for all students, we can enhance lifelong science learning.

It is especially crucial to be attentive to the diversity of worldviews in student populations at this juncture in the history of science education. Our new understanding about the learner has an enormous potential for bringing about radical change in the science curriculum. In order for science education to be equitable for all students, the new consensus about the learner makes it clear that instruction must respect the diverse views likely to be found in science classes.

Learners Construct a View of Themselves

One of the great challenges for educators will be to prepare students for a lifetime of autonomous learning.

There is growing consensus among researchers from psychology, anthropology, philosophy, education and other disciplines that learners construct a view of themselves, just as they construct beliefs about natural phenomena. This view is reflected in the individual's self-esteem, self-confidence, autonomy and personal sense of competence. It affects how learners monitor and regulate their learning. It determines motivation and effective effort in instructional settings. Furthermore, it is likely to persist.

The learner's sense of self governs his or her choice of experiences and, therefore, his or her educational opportunities. For example, students who believe they lack competence in science avoid experiences that could enhance their competence. They may fall further behind their peers who engage in these experiences. Those who believe they lack proficiency in the use of technological tools tend to gain less experience in these areas and are less prepared for new experiences when they arise.

As science becomes more complex and technology becomes more central to their lives, learners will increasingly be called upon to master information that becomes available after they have completed their formal schooling. One of the great challenges for educators will be to prepare students for a lifetime of autonomous learning. Since learners' beliefs about themselves affect how they respond to instruction, science educators need a better understanding of this phenomenon.

Self-Regulation

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Students can construct an understanding of their learning processes. Those who know how to monitor and regulate their learning are far more effective than those who do not. For example, learners taught to reason about their new knowledge and to question how it fits with their current ideas gain greater understanding than those who are not encouraged to reflect on their own learning.

Empirical studies show that teachers can encourage students to learn how they integrate their ideas by having them examine the links between one idea and another and reflect on the adequacy of those links. Students who are taught to construct and monitor their own learning this way are far more successful than those who lack this instruction. Instruction focusing on complex skills such as planning problem solutions can emphasize self-regulation.

A learner's sense of self influences this process. For example, one student might interpret his or her errors merely as evidence of failure. Another might realize that errors can provide valuable information for subsequent problem solving.

Developing a Powerful View of Oneself

A student's success at developing a positive view of himself or herself and a capacity for self-regulation depends on the learning environment. If students are rewarded for constructing their own understanding of a topic or for integrating information, they are more likely to display self-regulatory processes. Research and observation reveals that students in science are rarely motivated to learn the material that is being taught. Yet, unless students become engaged in learning and responsible for solving problems, they will not construct a theory of how they learn and will not get feedback on their self-regulatory processes. Rather, they will learn only to do what they are told.

Recent research has begun to identify factors that elicit students' curiousity and encourage them to solve problems on their own. Considerable individual differences in response to subject matter are expected, given that learners respond differently depending on their world views. Instruction involving an element of surprise or tension for the learner increases the likelihood that the learner will take on a problem and feel personally responsible for its solution, presumably because learners desire to incorporate new information into their world view. Aesthetic factors can attract students to the learning situation. For example, large differences in scale can attract learners: children often like large dinosaurs and are intrigued by the size and nature of the galaxy; they like the challenge of incorporating these phenomena into their world view.

Refinement of Methodologies

Science education has incorporated methodologies from many disciplines to help understand the complex tasks students and teachers face. These include the methods of Piaget, developed for understanding how students conceptualize complex scientific phenomena, methods from cognitive science for modeling student behavior, and methods from sociology, anthropology, and clinical psychology, developed to capture interpersonal interactions. A current concern is to identify how these methods can be made less cumbersome and more reproduceable.

A new view of what constitutes evidence has emerged along with the new consensus about the learner. By refining available tools and developing new ones, researchers and pre-college teachers are examining student performance at a level not previously emphasized. There is greater concern with the details of the child's world view and with the ramifications of those details. For example, close examination of how students learn topics like Pascal programming or geometry have revealed serious deficiencies in student knowledge. By observing the instruction received, the textbook content, discussions with peers, and difficulties encountered in solving problems, researchers have found that students are taught rules of geometry or the language features of Pascal but are left to figure out how to construct a problem solution essentially on their own.

A New View of the Curriculum

All that we have learned about adapting to the "information age" and all that research has revealed about the learner calls urgently for sweeping change in the science curriculum.

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Response to better understanding of learning must be immediate and extensive if we are to sustain high educational standards. Curricular innovation requires the collaboration of experts in subject matter, learning, instruction, and classroom practice. Materials designed on the basis of research findings and previous experience must be refined on the basis of instructional trials.

The information explosion changes the nature of knowing from the ability to recall information to the ability to define problems, retrieve information selectively, and solve problems flexibly. Rapid advance changes the nature of learning from the need to master topics in class to the need to learn autonomously. Educated citizens need to know how to revise their ideas and how to locate and synthesize information.

The Goals of the Curriculum

The goals of the science curriculum need to be redefined and broadened to reflect new knowledge, technological advances, and societal needs. It is not sufficient merely to increase science course requirements in the name of science proficiency.

The goals of the science curriculum need to be redefined and broadened to reflect new knowledge, technological advances, and societal needs. It is not sufficient merely to increase science course requirements in the name of science proficiency. There is widespread agreement that citizens need better instruction than they are now getting to reason and to vote intelligently about a broad range of scientific issues.

Current evidence suggests that science courses train scientists far more effectively than citizens. New findings about the role of reasoning specific to a given discipline imply, for example, that instruction emphasizing Ohm's law will not readily translate into effective reasoning about energy conservation, or that learning formal symbolic manipulation skills in algebra will not readily translate into mastery of formal skills in other mathematical domains. Science courses will attract more students and prepare them better for the 21st century if all emphasize science for the citizen while others also emphasize science for the scientist. Recent efforts to create a core curriculum in science reflect this trend.

Motivating the Full Range of Students

The factors involved in motivating students are now better understood than they were a decade ago and should be incorporated into curriculum research and instructional design.

It is essential to reverse the trends of lower enrollment in science courses and students' lack of motivation to study science. Science education research ought to explain how students can be attracted to the field, how they can be encouraged to pursue education in science that is appropriate to their needs, and what scientific knowledge they should have.

Particular effort should be focused on students in grades 4-8, because many lose interest in math and science in these grades. Modification of the experiences students have at this age can go a long way towards setting the stage for effective subsequent learning. Furthermore, the flexibility of the curriculum and the instructional setting in these grades make it an ideal time for investigating the effects of changing the motivational factors and the accompanying curriculum materials and evaluating their impact. For example, curricula that respond to students' concerns about the impact of science on society seem especially promising.

Research also needs to be done to determine what leads some students to develop a lifelong interest in science. Models of success in motivating students over longer, more realistic time scales are needed. Learning and motivation must be jointly understood. We need to reap the benefits of motivational research conducted by psychologists and sociologists and incorporate the findings of these investigations.

We should also harness the motivating potential of computers and learn how to use it to achieve the new goals of science education.

To help students construct responsible and robust world views as well as productive views of themselves, researchers concur that covering a few science topics in depth rather than many in a fleeting fashion will have a more lasting impact.

Depth versus Breadth

To help students construct responsible and robust world views as well as productive views of themselves, researchers concur that covering a few science topics in depth rather than many in a fleeting fashion will have a more lasting impact. Historically, at conferences such as the 1959 Woods Hole meeting, researchers and educators alike have remarked that students can "learn more by learning less." The new consensus about the learner provides direction for deeper coverage of science topics. Such coverage makes it possible for instructors to emphasize the problem solving skills and self-regulatory skills that students need. Students can link their new ideas to related ones and establish which ideas are encompassing and which are specific. After learning some thinking tools, students can take responsibility for answering their own questions, when subjects are studied in depth.

Empirical research demonstrates that students find in-depth coverage of a few topics more satisfying than superficial coverage of many. Students tend to develop "ownership" of problems and learn more when they are studying them over time. In contrast, superficial coverage often does no more than familiarize students with the terms rather than the theories and methods of science. Emphasis on problem solving in mathematics and science education is a step in the right direction.

Study in depth is consistent with the new consensus about how learners change ideas. Such coverage is more likely to modify students' belief systems by providing integrated understanding of a science topic. Integrated understanding is more likely to compete successfully with well-established but inaccurate intuitive beliefs.

Our understanding of the link between reasoning and subject matter implies that topics selected for in-depth coverage in science classes should reflect the fundamental problems of the discipline. The discipline-specific information imparted must have wide applicability. Those topics selected must serve as models that learners can use to master new topics after leaving school.

Integrated Knowledge

The traditional high school sequence of science courses often fails to consider that students are constructing a world view and fails to emphasize the interdependence of scientific disciplines. Students learning biology need to integrate knowledge about the chemistry of the cell; those learning geology need a sense of the particulate theory of matter.

The current school sequence of courses reflects the decision to offer a single science discipline for an entire school year. One result of this approach is that students taking the minimum number of science courses are never introduced to the fundamental issues in some disciplines. In order to change this tradition of science information delivery, it will be necessary to change textbooks, a particularly difficult task, but one which is likely to bring the goals of the curriculum much closer to the needs of the learner and to those of society. It will also be necessary to change how teachers present the curriculum, by structuring instruction such that related ideas are linked together.

To help students construct broad and reliable worldviews, courses should introduce and integrate fundamental concepts in biology, chemistry, physics, and earth sciences early in the curriculm and reinforce them in subsequent years. The experience of other countries suggests that students benefit when at least physics, biology, and chemistry are introduced early in the precollege curriculum and expanded subsequently. This approach permits all students to grapple with the topics central to each discipline. Revising the science curriculum in this way does not require that one teacher be responsible for every scientific discipline. Rather, for example, a chemistry teacher would offer shorter courses to freshman, sophomores, juniors and seniors rather than a one-year course only for juniors.

Test Design to Reflect Advances in Curriculum Design

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Research indicates that teachers "teach to the test". Clearly, testing programs could effectively eliminate the impact of new goals for the curriculum, if assessment measures do not reflect curriculum reform. Studies of innovative approaches to testing suggest that tests can be devised to evaluate the new goals for the curriculum effectively.

At present, standardized tests show that students acquire little lasting or useful knowledge in science classes. It is therefore not surprising that students who study a few topics in depth do as well on survey type standardized tests as those who study a smorgasbord of topics. The effects of providing depth rather than breadth would be even more impressive if tests were designed with deeper coverage of topics in mind.

Innovative tests that assess students' problem solving and self-regulatory skills are needed. Assessment of problem solving is only appropriate if students know enough about the variables to solve the problems. For example, students cannot solve problems about the impact of earthquakes if they lack understanding of plate tectonics. It is pointless to evaluate problem solving skills if students lack coherent understanding of the topic, because the test will reveal only the lack of topic knowledge.

At present, teachers can justify breadth over depth because current tests do not measure the reasoning and problem solving involved in covering topics in depth. If teachers were to select topics for such coverage from those central to the discipline and could pick assessment devices to match their choices, emphasis on reasoning and problem solving could be rewarded. Students could be encouraged to develop a productive view of themselves if they were assessed based on their ability to investigate a question related to the topics they studied rather than on their recall of information.

Situational tests, work samples, online computer-presented problem solving situations, and personal diaries are among the instruments that might prove effective for assessing revised goals in the science curriculum.

The same methodological tools that permit researchers to investigate reasoning offer promise for test developers. Computer simulation environments that allow students to reason about important and complex problems have potential for testing. On-line databases are promising as testing environments, especially because they could be used to assess ability to locate information. The elements of a new scholarship of test design are available, but they need elaboration and integration with educational policy and practice.

A New View of Teaching

Knowledge of the discipline is central to effective pedagogy, for teachers cannot help students recognize flaws in intuitive thinking or introduce concepts without deep understanding of the topics they are asked to teach.

As our understanding of learning and instruction grows, a new view of the teacher's role is emerging. The teacher's perspective about the learner and the subject matter determines how instruction proceeds. Yet, teachers receive little guidance while constructing an integrated view of the discipline they teach, the learners they serve, and the institutions employing them. Furthermore, little is known about what constitutes effective worldviews for teaching or how teachers can help students develop productive beliefs about themselves.

Much of teacher education reflects the belief that general pedagogical skills can be applied independent of discipline. The new consensus about the learner suggests that such a belief is unjustified, just as it is unjustified to presume that students can reason about a new discipline without discipline-specific knowledge. Knowledge of the discipline is central to effective pedagogy, for teachers cannot help students recognize flaws in intuitive thinking or introduce concepts without deep understanding of the topics they are asked to teach. Yet teachers often lack even a rudimentary understanding of the topics they must teach. They need time and help to develop a comprehensive view of subject matter.

Teachers need to understand the discipline they are teaching well enough to generate new insights over time. They need to understand the key ideas and their relationships to each other. They need to understand how students will react to those ideas. They need help in constructing a curriculum from the materials available and in developing a view of the learner specific to those materials. Expert teachers have this ability and the requisite knowledge, but these gifts are not easy to capture or to communicate to those entering the profession. Longer apprenticeships focused on such issues would allow experienced teachers to nurture entering teachers. Preservice and inservice teacher education focusing on the topics included in the pre-college curriculum can help in this regard. Career long professional development is required.

Teacher Workload and Isolation

At present, the pre-college teaching environment does not foster the development of stronger teaching skills. A wide range of programs have demonstrated that teachers construct more powerful views of their discipline and of the learner by sharing ideas. Teachers demonstrate considerable change in behavior and understanding as a result of sharing instructional strategies, and they develop new approaches as a result of sharing ideas with others facing similar problems. Similarly, when teachers and researchers share ideas, research findings can be communicated effectively. Yet heavy workloads and isolation militate against these experiences. The current pre-college setting requires an enormous number of student contact hours, far exceeding those required in colleges and universities. In addition, teachers are often preparing for four or five different classes, further expanding their workload. Given these demands, it is unreasonable to presume that teachers will also find time to share ideas with colleagues, interact with researchers, and participate in inservice teacher education programs.

Implementing the New Goals for the Curriculum

The new goals for the curriculum cannot be implemented unless they are introduced into teacher education programs and incorporated into curricular materials.

Textbooks must be revised, and needed technological tools developed. Materials and technology must be integrated. Researchers, curriculum developers, and teachers should cooperate in this effort and should seek to assure that decision-making is driven by educational goals, not marketing objectives.

Exploiting the New Technologies

Computer technologies enable students to perform tasks that are very different from those they had to do in the past, and they demand new skills.

Just as computer power has transformed the workplace and our daily lives, so have new technological tools altered the activities of students and the goals of education.

Computer technologies enable students to perform tasks that are very different from those they had to do in the past, and they demand new skills: planning solutions using software rather than manipulating equations, for example.

The new technologies make it possible to deliver instruction in fundamentally different ways and allow for the possibility of radically different learning environments. The key features of the technological learning environment include feedback on complex problem solving using programming languages, simulations, and other computer learning environments, opportunities to move quickly from one representation (like an equation) to another (like a graph), and access to larger databases. Research is beginning to show how aspects of technology can be exploited to help students gain more robust and informed views of science disciplines.

The new technologies provide researchers with far more powerful tools than ever before for studying how students learn. In the computerized laboratory, there are both more opportunities to control how students engage in learning and more possibilities for diversifying the sort of information to which they respond.

The degree of motivation, imagination, and curiousity engendered by computers is exceptionally high.

When curriculum materials in science education are presented by computers, the various instructional elements can be selected with great precision and be systematically investigated. For example, researchers can vary the features of the curricula and assess their separate and combined impact on learning. They can design learning environments and examine how students generate hypotheses and test their ideas.

The degree of motivation, imagination, and curiosity engendered by computers is exceptionally high. By varying curricular provisions, researchers can investigate factors that encourage students to develop a productive view of themselves.

Curricular Change

Because the new technologies provide precise, interactive feedback, they encourage students to approach problems through trial and revision of ideas. Innovative programming environments offer online feedback about potential errors in the logic of a program. Simulation software offers online feedback about electrical circuit design, geometry problem solving, and other topics. Interactive videodisk allows rapid comparison of geological phenomenon. All these contribute to the desired depth of coverage in the curriculum.

Computers allow students to learn to use rule-based systems, such as programming languages, to solve problems. Creative technological tools in conjunction with powerful curricula ensure that students develop a robust understanding of such systems. By learning several programming languages, for example, students gain general skills in using algorithmic techniques such as recursion to solve problems. By becoming proficient in one language or system students can define their own procedures and see how they perform under different conditions. Researchers are inventing formal systems that allow students to develop similar understandings in other disciplines such as biology.

A variety of simulations and graphing tools encourage students to think differently about science. Empirical research demonstrating the advantages of relating different problem representations to each other can be evaluated in the computer environment. Consider science labware that permits students to observe the graphic representation of their data while the experiment is progressing. Students might compare the rate of cooling of 100 grams of water in aluminum and styrofoam. This innovation clearly reduces the memory load required for understanding the relationship between the experiment and the graph. It also provides a dynamic representation of a complex relationship. Thus, students understand the graphic representation of data by linking the graph of their experiment to the physical set-up of the experiment. Similarly, a computer simulation can quickly relate different problem representations, such as chemical reactions, to the differential equations that describe the changes in concentrations and to the graphs showing those concentrations. Computer programs can depict algebraic relationships by permitting students to display graphs of several different equations simultaneously on the screen. Research demonstrating the effects of these new technologies is just starting to emerge.

Students who are systematically exposed to databases and database management systems may develop skill in locating and using large bodies of information. Using databases, students can examine and tabulate information such as migration patterns of birds, temperature patterns of the ocean, and weather patterns of the world. Science curricula would be greatly enhanced through access to such complex information in a readily digested form.

A variety of technological tools reduce the workload for students. Word processors and electronic spreadsheets relieve students of the need to focus attention on technical details and permit them instead to concentrate on the problems they are solving.

Researchers have built expert systems to solve problems and compared their behavior to that of science students. By designing such systems, researchers generate hypotheses about how students solve problems. Comparisons of expert system problem solutions and human problem solutions can address such questions as what is general knowledge and what is specific knowledge.

Integrating These Research Themes

In order for the new thrust in science education research to have the greatest impact, researchers, educators, and subject matter specialists with a broad range of perspectives must seek to unite its many themes.

A teacher laments, "I know how to be a better teacher than I am." Researchers might reply, "I know how to be a better researcher than I am."

In order for the new thrust in science education research to have the greatest impact, researchers, educators, and subject matter specialists with a broad range of perspectives must seek to unite its many themes.

If we succeed in integrating our understanding of the learner with our understanding of the process of instruction, the training of teachers, the curriculum, the instructional setting, the role of technology, the role of curricular materials and the testing of students, we will have built a strong foundation for needed innovations in science education.

3 Recommendations

Research advances since the middle of the century have improved our understanding of cognition and have suggested ways in which formal instruction can be tied to the student's own learning process.

As science educators and researchers in an age of accelerating technological innovation, we have a critical responsibility to prepare students for adult lives which will be constantly tested by change and challenged with new information.

Research advances since the middle of the century have improved our understanding of cognition and have suggested ways in which formal instruction can be tied to the student's own learning process. We must refine these insights, increase our understanding in other areas, and integrate our findings to create a body of knowledge which will serve as a basis for practical improvements in science education.

In light of these challenges, and in keeping with the state of the research enunciated at this conference, we submit the following four recommendations:

1. Establish Centers for Collaboration in Science Education

There is a critical need for greater interaction among professionals involved in science education. The new research in science education draws from a broad range of perspectives, and the progress that has been made reflects the combined effort of people who only recently have begun to collaborate. Experts in such areas as cognition, science education, pre-college teaching, the subject-matter disciplines, and curriculum design, need the opportunity to work together to define goals and objectives, develop common definitions, plan programs, and exchange ideas. We need to synthesize the knowledge of these diverse researchers into a cohesive science. To accomplish this, they should be able to meet and collaborate in an environment conducive to productive interchange.

Centers for Collaboration in Science Education would provide the environments and incentives for greater collaboration in science education. In addition to fostering research and communication among professionals across disciplinary lines, Centers would provide a unique setting for training science education researchers and preparing pre-college teachers.

Centers for Collaboration in Science Education must assemble the best possible talent, attack the most pressing voids in science education, and support visits of significant length from researchers, precollege teachers, subject-matter specialists and curriculum designers. Centers must establish mechanisms that ensure joint consideration of central issues in the field, regular review of progress, and frequent reassessment of priorities. Centers should have flexible structures that allow redivision of energies and redefinition of emphases as our knowledge expands. Centers should support intensive collaborative projects that bring together individuals from different locations for reasonable periods of time.

Centers might have differing special perspectives within science education a focus on mathematics curricula, computer science curricula, or science problem-solving, for example--but all would pursue in common the following research objectives:

- *identify new goals for science education*
- *develop and refine our knowledge of learning and instruction*
- *develop and test experimental curricula*
- *identify ways to use new technologies for instruction*
- *evaluate the effectiveness of these innovations in instructional laboratories which would serve as prototypes of the school of the future*
- *develop and evaluate new methodologies for assessing student learning*
- *create and evaluate new teacher training methods in science education*
- *examine innovative practice in the community and encourage collaboration with pre-college teachers.*

2. Expand Opportunities for Sharing Information

Better communication is critical to progress in science education research. Many of the leaders who attended this conference met each other for the first time. Mechanisms must be developed to give researchers and educators more opportunities to exchange ideas face-to-face and to share information among projects. Electronic communication should be encouraged and supported.
Professional newsletters and journals should expand the effort already underway to feature contributions from different perspectives and to sponsor special issues focusing on areas for possible cooperative research.

More conferences such as this should be held to encourage communication and information sharing across disciplines and to build communication networks. The means should be found to enable creative and talented pre-college teachers to participate.

3. Increase Fundamental Understanding of Science Learning

To build a strong foundation for needed innovation in science education we must understand the nature of science learning. Researchers studying basic processes of cognition and learning should accumulate fundamental knowledge about science education. Researchers need to explore in greater detail such questions as how students develop a world view, reason about new information, and solve problems in science. The research community should seek to integrate varying perspectives on these issues. Research should reflect deep knowledge of subject matter and conditions of practice in science education. In particular, subject matter experts and pre-college teachers should contribute. In examining the learner, researchers should take into account the wide range of populations and diversity of subcultures that characterize our nation.

4. Strengthen Response to Instructional Needs

Research in science education should reflect and respond to real instructional needs. Science education research must develop a body of basic knowledge and methodologies that are relevant to and inform the practice of science education.

Methodologies should be developed to ensure more effective and timely use of research findings. Research conducted in real educational settings provides new insights into the nature of cognitive and instructional processes, allows for study of the social and cultural factors that influence learning, permits trial and refinement of innovations and is thus far more likely to influence science education practice. Research using case studies and work samples to gain detailed, longitudinal understanding of teaching and learning provides understanding of the multiple interacting factors that influence learning.

It is critically important to encourage science learning among the diverse populations of the United States and to meet individual needs as well. Researchers should be sensitive to this diversity when they design curricula and instructional materials and when they evaluate the effectiveness of their programs and recommendations. They should also monitor access to new technologies for all cultural and population groups and should identify ways to ensure access for all who desire it.
To develop and sustain the new thrust in science education research, we must avoid the chronic amnesia that often characterizes research in education. The curriculum efforts of the past, particularly the large projects of the 1950's and 60's, attempted to accomplish many of the same objectives that are central to the new thrust in science education research. Research and instructional development conducted now should be informed by the results of those efforts. Past efforts should be evaluated with the same breadth of perspective that informs current research, using new approaches, such as indisciplinary case studies or histories, to augment traditional evidence such as test scores.

4

First Steps Toward Implementation

Let us take stock of our resources, muster our considerable energies, and invite each other to begin.

With each graduating class, another generation of students goes forth to face a lifetime of learning, armed with whatever tools its teachers have provided. To help science teachers meet this awesome responsibility with techniques and information appropriate for the new age of science and technology, the science education research community must agree upon common goals and develop plans for action, such as those embodied in the recommendations above.

We propose the following steps for implementing the recommendations of this report as quickly as possible:

1 *Develop a model for Centers for Collaboration in Science Education that specifies the nature of collaboration.*

2 *Determine how such centers can be funded.*

3 *Create forums at national meetings to discuss the recommendationsin this report and develop specific action plans.*

4 *Review the progress being made towards achieving the recommendations at a follow-up conference to be held in 2-3 years.*

We are at an important juncture in our efforts to improve science education. By integrating the contributions of the many groups involved, it will be possible for u to build a body of knowledge that will provide guidance for designing better curricula, improving teacher training, creating innovative instructional settings, an achieving the level of scientific education that students need and deserve. Let us take stock of our resources, muster our considerable energies, and invite each other to begin.

5

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