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ABSTRACT

This volume, part of the EDThoughts series, was authored by science education specialists from across the United States of America. It addresses approximately 50 questions identified by science educators, including "Can all students learn science?" and "What is the importance of reading and writing in the science curriculum?" Teaching using inquiry, technology as tools of scientists, and teaching in a standards-based science curriculum also are discussed. The purpose of the book is to support standards-based reform of science education. For each question addressed, background is provided from the perspectives of research and best practices, followed by implications for improving classroom instruction. (Contains 11 pages of references and resources.) (MM)

EDThoughts

What We Know About Science Teaching and Learning

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EDThoughts

What We Know About Science Teaching and Learning

edited by
Alice Krueger and John Sutton
Mid-continent Research for Education and Learning

McREL

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Dear *EDThoughts* Reader,

Many good intentions have gone into ambitious education reform goals, including those ratified by the U.S. Congress in 1985. But the year 2000 deadline has passed, and our nation has not made measurable progress toward the goal of becoming "first in the world in mathematics and science education."

In international comparisons, our students' overall mathematics and science achievement is mediocre. The Third International Mathematics and Science Study (TIMSS) from 1995 showed our 3rd- and 4th-graders scoring above the international average but our 12th-graders scoring well below. The TIMSS-Repeat results released in 2000 do not show significant improvement. What can we do to make a difference?

EDThoughts provides a place to start. The mathematics and science *EDThoughts* books summarize educational research and surveys of best classroom practices, and they offer implications for improved teaching and learning.

Classroom teachers and K-12 administrators will find these books useful for their own professional development; teacher educators can use them to inspire their students; and parents and the public may discover the effects of present and proposed practices on future generations. Effective reforms in mathematics and science education practice and policy will require the collaboration of all of these stakeholder groups. They will need a common understanding of the current status of mathematics and science education and of the direction that research and best practice indicate for improvement as well as how they can help accomplish reform. We hope that this book provides a foundation for greater understanding and reflection.

Please take a moment to fill out and return the postcard enclosed in this volume. You then will be sent a short survey that will help us to design useful supporting materials and products and to keep this document fresh. Your participation is sincerely appreciated.

Signed,

John Sutton	Alice Krueger	Jim Woodland
McREL	McREL	CSSS

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Preface

The world around us is changing rapidly. There have been changes in how people live, work, and learn. Likewise, the culture and practice of science continue to evolve. Science is conducted less in bounded disciplines like physics or biology and more in transdisciplinary research fields, of which there are over 400 in the area of biology alone. Advances in technology were once generated by discoveries in science; now current technology may limit scientific inquiry. The demand for applications of science in daily life influences its development and raises perplexing questions. Science increasingly concerns itself with ethics and values.

Corresponding to changes in science, there have been over 400 science education reform documents published since 1970. Education reform connects instruction to new forms of information, especially the Internet. As students increasingly are educated to become lifelong learners, they must develop skills to manage and use knowledge to solve problems in the personal, social, and economic realms, not just in textbooks. Today's students will need to build their capabilities for career changes more so than at any time in the past. Most twenty-first century careers are knowledge-based, not skill-based. Knowing how to access, evaluate, and use information is a major component of literacy.

The concept of "scientific literacy" was first voiced by biologist and educator Paul Hurd in 1958. Science literacy is defined in the context of the current society, thus recognizing the interactive relationship between science as a discipline and the society in which it is practiced. More recently, Nobel Laureate Glenn Seaborg worried that high school graduates were foreigners in their own increasingly-scientific culture, because they did not have an adequate working knowledge of science. National science education standards describe what a literate high school graduate should know and be able to do to serve well as a citizen who makes decisions about matters dealing with science topics.

The primary purpose of science education is to prepare future citizens for informed decision making. If the scientist is a broker of scientific knowledge, providing basic information, suggesting its utility, and identifying risks of using the information, the science student is a consumer of this information. Only about two percent of science students will become scientists. The emphasis of instruction in science classrooms should be on the future (using science for solving society's dilemmas), not on the past (science taught as a history of the discipline).

The purpose of this volume is to support standards-based reform of science education. For each question addressed, background is provided from the perspectives of research and best practices, followed by implications for improving classroom instruction.

Teachers need the findings from research and best practices to inform their daily decisions. Part of the decision-making process requires teacher expertise (knowledge and experience) in determining whether the practices being considered for adoption would work in their own classrooms. Using data to drive instructional decisions improves the efficiency of reform efforts by focusing change in the desired direction toward improved student achievement. It is ineffective for teachers to base decisions on anecdotal information or individual cases.

The authors of this volume strongly support standards-based systemic reform. They recognize that the national science education standards describe not only important curricular content, but additional ways to reform all parts of the educational system to support improved teaching and student achievement. Systemic reform purposefully revises and aligns all components of a system. The science education system is complex, including components such as assessment, curriculum, equity, student outcome standards, teaching, professional development of teachers, stakeholder involvement, leadership, and policy. While the last three topics are generally beyond the scope of this volume, they are important in the context of standards-based systemic reform.

Every person concerned with teaching and learning science, whether teacher, administrator, student, parent, or community member, will find useful information in this document. As the nation moves forward in reform of science education, we must not forget lessons learned from research and best practices. These will guide us toward the improvement of our students' achievement that we cannot afford to miss.

About the *EDThoughts* Books

The format of this series of books is intended to bring to K-12 educators the rich world of educational research and best practices. As classroom teachers are mainly concerned with what works in their own classrooms, these documents balance reporting research results with drawing implications from it. Thus each pertinent question is addressed through both a page of Research and Best Practice and a page of Classroom Implications.

The background research and related documents for each question are cited in compressed format in the margin bar on the right page. There is a full citation of all References in the back of the book to allow the reader to examine the primary source documents. In addition, for those desiring deeper professional development on any of these questions, a list of additional Resources is also available. It is the intent of the authors that the format of the *EDThoughts* books will encourage classroom teachers to delve into the available results of educational research and apply the findings to improve the achievement of all their students.

The list of authors for the *EDThoughts* science and mathematics books includes state content consultants belonging to both the Council of State Supervisors of Science (CSSS) and the Association of State Supervisors of Mathematics (ASSM), and mathematics and science experts from several Eisenhower Regional Consortia. The editors belong to Eisenhower Regional Consortia, Regional Educational Laboratories, and other national organizations. With such wide geographic representation among authors and editors, the reader may expect to find an equally wide range of perspectives represented.

There are unifying threads throughout all the articles. One common element is the authors' reliance on the national standards, both the NRC *National Science Education Standards* and the AAAS *Benchmarks for Science Literacy*, as compilations of best practices. It would have been possible to list these standards documents as References on every question. Another common theme is the importance of quality science education for all students. The reader will also notice the frequency with which professional development needs are stated in the Classroom Implications sections. The presence of these common themes shows the consistency of approach of the diverse authors.

Science For All

All students can learn science, and they deserve the opportunity to do so. National standards – set forth in the *National Science Education Standards* (*NSES*) and *Benchmarks for Science Literacy* – define science literacy expectations for all students. Content standards describe what all students are expected to learn. However, recognizing the diversity among the nation's children, educators do not expect all students to learn the material in the same manner, using the same materials, and in the same time frame. To quote the *NSES:*

> *The Standards apply to all students, regardless of age, gender, cultural or ethnic background, disabilities, aspirations, or interest and motivation in science. Different students will achieve understanding in different ways, and different students will achieve different degrees of depth and breadth of understanding depending on interest, ability, and context. But all students can develop the knowledge and skills described in the Standards, even as some students go well beyond these levels. (p. 2)*

To achieve "science for all" will take a concerted effort of all stakeholders in our childrens' education. We must continue to make progress toward providing rich, well-supported learning environments that respond to the unique educational needs of every student. This is the goal of science education reform.

What is equity and how is it evident in science classrooms?

The focus of an equitable science program must be on student outcomes.

Research and Best Practice

An equitable science program provides high-quality science education for all students. Students not only have access to quality science courses and instruction, but they also have the support necessary to ensure their success in the courses. Equitable school programs must ensure that student differences in achievement will not be based on race/ethnicity, gender, or physical disability, and appropriate instructional support must be provided for all students to ensure success for all.

A common perception of equity in science is that all students should be provided equal opportunity and access to science classrooms. While this is commendable, opportunity and access are not enough to ensure that all students achieve desired outcomes. To ensure student success, an educational system must focus on student outcomes and provide the support necessary for students to achieve those outcomes. Since different students learn in different ways, equal treatment for all students does not guarantee equal success. The greatest student success occurs with different instructional strategies addressing the learning needs of all students. Students must be provided equal opportunity and access to science classes, while receiving the support necessary to be successful in those programs.

Current science reform initiatives stress achieving excellence through systemic school reforms. These reforms, though commendable as goals, often do not address issues of equity. Higher standards and alternative testing are often not accompanied by the resources and school support needed to increase the achievement of underrepresented groups of students. School reform that emphasizes science for all students will entail a fundamental restructuring of the science program and other aspects of education as well. Research indicates that effective schools have a clear school mission, strong building leadership, a supportive and safe school climate, specified classroom curricula and instructional methodologies, frequent monitoring of student progress, and positive school/community relations. Varied instructional strategies for delivering high quality content to all students will be a part of every classroom.

Classroom Implications

The focus of an equitable science program must be on student outcomes. Teachers and principals are responsible for the achievement of all students, and consequences for lack of student success fall not only on students, but also on teachers, principals, and whole schools.

A variety of instructional methods should be used by teachers to reach all students with high quality content. These strategies will

- Address different student learning styles
- Encourage the participation of under-represented students
- Support students in constructing their own understanding
- Challenge all students
- Encourage diverse student cooperation
- Encourage the use of inclusionary language in all classroom communication
- Involve parents in student learning

Adequate knowledge of science content and pedagogy is essential for teachers to effectively address the needs of a diverse group of students. Assessments need to be analyzed for bias and must be fair to all students. In-service teachers should regularly take advantage of content-specific professional development to enrich their content knowledge and to stay abreast of the latest teaching techniques.

The physical environment of the classroom should be interesting and inviting for all students. The classroom should display student work and other material representative of gender, race, culture, and physical disabilities, and show a diverse group of people involved in science activities and careers. The classroom arrangement should allow all members of the class to participate in learning activities. For example, all students learn to use equipment; develop their ideas; discuss observations and results; and operate computers.

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What are the impacts of ability grouping and tracking on student learning?

As the demands for a more scientifically literate society continue, schools need to respond to the challenge of providing more meaningful science to more of our students, more of the time.

Research and Best Practice

Tracking and ability grouping are used to provide differentiated, developmentally appropriate instruction, but rarely allow for upward movement between tracks or groups when a student makes developmental leaps. Hence, a conflict exists between the structure of academic tracks or ability groups and the academic and intellectual growth of students. The student should be the reference point for addressing the complex issue of who should learn what science and when. The profound question of whether or not to "sort" students encourages educators to think about the implications of placing students in various ability groups or tracks for science instruction. Will the students benefit or continue to struggle?

The structure of instruction in the lower tracks tends to be fragmented, often requiring memorization and filling out worksheets. Although some higher track classes share these traits, they are more likely to offer additional opportunities for making sense of science, like class discussions, writing reports, journaling, and real-life science applications.

Traditional tracking is not the only practice available to educators that allows differentiated instruction. In a differentiated heterogenous classroom approach, teachers assess student needs and design the delivery of content based upon students' understanding of science using a variety of instructional strategies that focus on essential concepts and skills. Inherent in this practice is the opportunity for all students to receive quality science instruction while in a heterogeneous group.

Practices in teacher assignment contradict the mantra of science for all. Indications are that teachers with the least scientific background instruct primarily the lowest performing students in science. Studies also suggest that expectations placed on students differ according to their assigned track or ability group. Students deemed less capable, experience less science.

As the demands for a more scientifically literate society continue, schools need to respond to the challenge of providing more meaningful science to more of our students, more of the time. Education is not meant to sort students, but to help them uncover their hidden scientific talents.

Classroom Implications

For the teaching and learning of science to be effective with students from a variety of previous science learning experiences and successes, teachers and school counselors must work within a framework that places student needs above schedules and predetermined tracks. The teacher must believe that all students can learn and that learning occurs in different ways and at different rates.

The study of science is an interactive endeavor, and therefore promotes divergent thinking within a classroom. Incorporating varied instructional techniques is essential for success of students participating in a mixed ability science class. The curriculum must be made meaningful to students by providing contexts that give facts meaning, teaching concepts that matter, and framing lessons as complex problems. Students need to socially construct knowledge, including regular opportunities to take risks, exchange ideas, and revise their understanding of science. Instructional strategies must be diversified to include all types of learners. To embrace multiple intelligences teachers must present information in a variety of ways.

Assessment must be varied as well as instruction. Use of performance assessments, keeping an ongoing portfolio of growth and achievements, projects demonstrating science understanding, solving complex problems in a variety of contexts, and student-generated inquiry are examples of varied assessment strategies.

Counselors can inadvertently schedule a student in an inappropriate course based on false assumptions (e.g., presumed equivalence of courses, placement based on numerical data rather than teacher recommendations). School counselors need more information from content specialists when creating students' schedules in the middle and high schools. This can provide a richer classroom experience and an effective way to enhance the learning of science for all students.

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What can schools do to facilitate students' opportunity to learn science?

"By emphasizing both excellence and equity, the Standards also highlight the need to give students the opportunity to learn science ... Responsibility for providing this support falls on all those involved with the science education system."

National Research Council, 1996, p. 2.

Research and Best Practice

Opportunity to learn (OTL) means maximizing learning for all students. OTL strategies include access to courses; a curriculum that meets content standards and is free of hidden bias; time to cover content during school hours; teachers able to implement content standards; adequate educational resources; respect for diversity; school safety; and ancillary services to meet the mental and social welfare needs of all students.

While other staff play roles in providing OTL, the teacher makes an immediate impact on several components. Teachers' attitudes and expectations are critical in determining how well students perform in the classroom. These expectations can increase or decrease a student's performance or effort. By varying instruction and understanding the differences in needs and learning styles of individual students, teachers facilitate a learning community for their students. A community climate improves student achievement. Effective climate depends heavily on access to a rich array of learning resources, hands-on materials, laboratory equipment, and space. This environment promotes group collaboration, essential to student-centered classrooms.

Opportunity to learn is also facilitated through student-centered classrooms focused on higher-order thinking skills, inquiry, substantive conversation, and real world context. Student-centered classrooms engage students in social and interactive scientific inquiry accomplished through evidence-based discussions and reflection on learning. Learning is an active process that allows students the opportunity to construct understanding through empirical investigation and group interaction.

Opportunity to learn is enhanced by linking student learning to their social and cultural identity, which assists students to better understand the subject being taught. The premise of culturally responsive curriculum and pedagogy is that a student becomes more engaged in content when that content is significant to their own cultural beliefs and values. Alaskan educators have developed programs based on local traditions focusing on science and mathematics. This approach has facilitated learning new concepts by using the cultural context with which students are already familiar. The programs incorporate a variety of female and minority role models in lessons to amplify students' confidence and comfort with the content being taught. These role models demonstrate that anyone can be successful in science.

Classroom Implications

Skilled teachers and school counselors can help all students achieve to their greatest potential. Their influence can convey high expectations and help raise students' self-esteem and performance. A standards-based curriculum implemented through creative use of classroom strategies can provide a learning environment that both honors the strengths of all learners and nurtures the areas where students are most challenged. By including science content from a variety of cultures and personal experiences, teachers enhance the learning experience for all students.

When instruction is anchored in the context of the learner's world, students are more likely to take ownership and determine the direction for their own learning. When the teacher, armed with opportunity-to-learn strategies, facilitates students' taking responsibility for their own learning, the result is an equitable learning experience. Consequently, students' science knowledge becomes connected to the socio-cultural context to create scientific habits of mind.

To foster good teaching and high student achievement in inquiry-based science, adequate resources for classroom instruction should be made available to all students. Balances, microscopes, and laboratory supplies for a rich variety of investigations should be used regularly by all students. Consumable laboratory materials should be replaced as needed, and equipment must be kept in good repair. Schools that support equal access to laboratory facilities, supplies, equipment, and resources are more likely to produce a student population with high scientific literacy.

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How can science activities and facilities accommodate students with disabilities?

Each student has something of value to offer the community of learners. It is the responsibility of the teacher to establish an atmosphere where all learners can contribute.

Research and Best Practice

Over ten percent of U.S. students are identified as having a disability and are served through an individual education program or plan (IEP). Legislation calling for equity in educational opportunity requires that students with disabilities have access to the general curriculum. As the number of students accessing the general curriculum in mainstreamed settings increases, the need for equipment, facilities, and instructional strategies to teach all children becomes critical.

Despite progress both legislatively and culturally, students with disabilities often lack the access to science learning afforded other students. One significant barrier is the design of the facilities for student's laboratory work, field investigations, and research. Another significant barrier is non-supportive teacher behaviors, including choice of instructional materials and strategies. In addition, students with restricted vision and hearing may have difficulty accessing instructional materials, media, and laboratory technologies.

Barriers like these can be overcome using adaptive technology devices that integrate a student into the classroom learning environment, as well as the culture of the school. Examples include Braille or "talking" measuring equipment and recorded textbooks. School facilities should provide sufficient space to create a rich learning environment. Facilities should accommodate materials and equipment set up for long periods for repeated use. Labeled displays of materials and equipment may create interest and familiarity for a student with a learning or emotional disability. Numerous, varied activities will provide students with the skills to achieve in science.

Almost half of all students classified with disabilities have a learning disability. A successful learning strategy for these students is cooperative learning, or students working as teams. Also, same-age grouping helps develop social skills. Cooperative learning, like many of the accommodations needed to provide students with disabilities access to learning, enhances learning for all students.

Classroom Implications

Teachers should assess all their students' needs to inform instruction, particularly for students with disabilities. Students are individuals whose talents and disabilities vary widely in range and severity. Expanding a student's talents is as important as making appropriate accommodations to overcome disabilities. Each student should be evaluated individually without generalizing, considering needs and preferences, facilities and available technologies.

Some accommodations that might be tried include

- Altering lab bench heights and maintaining space for students in wheelchairs
- Using tables instead of desks to encourage student collaboration
- Providing lab stools for students who need assistance for extended standing
- Acquiring electronic data collection devices for students with limited dexterity
- Using microscopes in conjunction with projectors
- Finding accessible field sites
- Assigning individual FM units for students with hearing impairments
- Using closed captioned videos and CDs
- Utilizing adaptive measurement devices and computer stations, including audio or tactile displays and text-reader software and graphical user interfaces
- Designating peer note takers or providing lecture outlines
- Installing sound-absorbent classroom materials to minimize echoes and background noise
- Avoiding instruction in front of windows or bright lights
- Creating sufficient space for collaboration in small groups and individual coaching

Despite good intentions, it is extremely difficult to anticipate all possible needs of students with disabilities. The science teacher is part of a team of professionals serving a student with an IEP. Teachers must be flexible about curriculum, provide appropriate accommodations, structure instruction around a variety of learning styles, and inquire into students' learning needs. Each student has something of value to offer the community of learners. It is the responsibility of the teacher to establish an atmosphere where all learners can contribute and to have a genuine concern for individual students' needs.

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How can different learning styles be addressed with consistent expectations?

"They're not dumb, they're different."
Tobias, 1990.

Research and Best Practice

Learning styles are collections of personal characteristics, strengths, and preferences, describing how individuals acquire, store, and process information. Learning style factors include information processing modes, environmental and instructional preferences, cognitive capabilities, and personality features. Individuals may demonstrate a balance among the dimensions of a learning style, or they may show strengths and weaknesses. Strengths and weaknesses may have implications for course success, and eventually for career choice. Groups of students from different cultures may exhibit distinct average learning styles, but there are often such broad within-group variations that generalizations about learning styles and cultural background are not reliable.

Learning styles not only influence how individuals learn, but also how they teach. Teachers often teach in the manner in which they had been taught even if it does not support the learning style preferred by most students. Teachers aware of their own teaching styles are able to make better choices of instructional strategies that do not impede learning. They can interpret students' questions, comments, and answers in the context of learning style variations. For collaborative group work, multi-style student teams will optimize inquiry and problem-solving.

It is important for students to know their learning style strengths and weaknesses and to develop a set of learning strategies to use their strengths and compensate for weaknesses. When instructed in the use of various learning strategies, students become more efficient and effective in their studying and more likely to attribute success or failure to their own choice of learning behavior rather than to their innate competency. Science teachers who have taught their students about learning styles find that they learn the material better because they are more aware of their thinking processes. Students conscious of learning style differences develop interpersonal communication skills critical to adult success.

Longitudinal studies of outcomes of instruction specifically geared to a broad range of learning styles show students have improved learning, increased satisfaction with instruction, more skill in applying knowledge, and enhanced self confidence. Science teachers should note that an inquiry approach incorporates aspects of various learning styles.

Classroom Implications

Learning style strengths and weaknesses can influence task success and overall achievement. Students should know personal learning strengths and weaknesses, and be able to use strengths to compensate for weaknesses. Tools for assessing learning (and teaching) styles are available. They can provide clues, not labels, to personal styles; learning styles are preferences, not traits or abilities. Students need to learn strategies for coping with varied learning environments and how to modify or generalize strategies for novel situations. Strategy use includes knowledge about the strategy, when to use it, and how to tell if it worked.

When there is a significant unaddressed mismatch between teaching and learning styles, students are inattentive, bored or discouraged, and perform poorly. In response, teachers may become overly critical, misinterpret poor scores as low ability (which exacerbates the situation), or become discouraged with teaching. Therefore, teachers must know how to identify learning and teaching styles, and how to teach various learning strategies. They can use differentiated instruction that is varied enough to meet students' needs while respecting diversity. Flexible teaching and assessing benefits learners who choose among standards-based learning methods and products.

If teachers teach exclusively in a student's less preferred style, discomfort may interfere with learning. However, students must experience non-preferred learning styles. Preferred styles are not static, and skill development in non-preferred modes provides advantageous mental dexterity. Learning in early stages of a curriculum unit may be more efficient using a different style than later in the same unit. It is important that the teacher balance instructional methods so that all students are taught partly in their preferred styles, but also practice learning in less-preferred modes. The teacher's choice of learning style typology within which to plan lessons is irrelevant. Teaching that addresses all dimensions ("teaching around the cycle") on most of the theoretical models is more effective than unidimensional teaching.

In assessing students whose learning will be demonstrated through different learning styles, it is important for the teacher to consider the criteria for success. Demonstrations may vary, depending on learning styles, but in a standards-based classroom, the expectations of content and process coverage may be met through any demonstration that addresses the standards.

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Teaching Science

Learning and teaching science are both complex, active processes. Teachers are constantly making decisions as they facilitate a daily learning environment in which they work with their students as active learners. They must also undertake long-term planning to connect daily efforts into the total education of each student. At the same time, they share responsibility for their students' success with other participants in the educational community, which includes other educators, educational institutions, and the policies of the educational system.

The *National Science Education Standards* (*NSES*) outlines theoretical and practical knowledge and understanding about science, how children acquire science content, and science teaching techniques that facilitate each child's learning. Effective professional development moves teachers toward the goals spelled out in the Science Teaching Standards. Because teachers' classroom decisions affect the achievement of each individual student, teachers need to avail themselves of strategies as varied as their students and their educational needs.

What instructional methods support scientific thinking?

"Good science inquiry involves learning through direct interaction with materials and phenomena. One important sign of inquiry is the relative level of control that the students have in determining various aspects of the learning experience."
Kluger, B.-B., 1999, p. 47.

Research and Best Practice

Scientific thinking is an important aspect of inquiry. In addition to asking questions, researching what is already known, planning and conducting investigations, recording observations, collecting data, developing explanations based on those observations and data, and communicating one's findings, it is critical for students to utilize scientific thinking. They must be able to identify assumptions, use logical and critical thinking, and be able to evaluate alternative explanations.

In order to develop scientific thinking skills, students must go beyond learning disconnected facts or simply doing a hands-on activity. Students are able to master scientific knowledge and processes while they use logic and reasoning skills.

Inquiry and the National Science Education Standards summarizes research findings on how students learn science. They include

- Students build new knowledge on what they already know Students formulate new knowledge by modifying their current concepts
- Learning is impacted by the social environment in which the learners interact
- Effective learning requires students to take control of their own learning
- The transfer of learning is affected by the degree to which students learn with understanding

These findings demonstrate the need to develop scientific thinking skills while learning subject matter.

Scientific thinking can also be enhanced through instructional methods such as identifying similarities and differences; summarizing and notetaking; nonlinguistic representations; cooperative learning; setting objectives and providing feedback; generating and testing hypotheses; and questions, cues, and advance organizers.

Classroom Implications

Scientific thinking skills must be developed throughout K–12 education. At the elementary level students are able to use their observations to create reasonable explanations for their questions. They are also able to conduct investigations in the form of a fair test. At the middle school level students will begin to recognize the relationships between evidence and explanations. Senior high students are able to analyze evidence and evaluate their own explanations and those of scientists.

Although there are many instructional models that support scientific thinking, most share certain aspects. They engage students in scientific questions, provide opportunities for students to explore those questions, require students to interpret data to create explanations, allow students to extend this learning, and evaluate what they have learned. Effective instructional methods promote student activities such as

- Comparing, classifying, and using analogies
- Analyzing and synthesizing information that leads to summarizing and notetaking
- Creating graphic representations or making physical models, drawing pictures and pictographs

Just as one cannot learn to write without being actively engaged in the writing process, it is impossible to teach scientific thinking without having students engaged in the process of doing science. At a minimum of once during each school year every student should complete one full investigation. This student-centered investigation should be designed to allow students to ask a scientific question, design and conduct a scientific investigation, use appropriate tools and techniques to gather and analyze data, develop explanations based on evidence, think logically to make the relationships between evidence and explanations, evaluate alternative explanations, and communicate scientific findings.

There are a variety of local, state, and national programs that support the development of scientific thinking skills. These include the traditional science "fairs," invention conventions, and a variety of other opportunities for individuals or groups of students to display their scientific work. These activities need to be linked with regular standards-based classroom activities.

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How is inquiry taught?

"Good science inquiry provides many entry points – ways in which students can approach a new topic, and a wide variety of activities during student work."

Kluger, B. -B., 1999, p. 47.

Research and Best Practice

The *National Science Education Standards* is clear about the importance of inquiry teaching and learning. It says science teachers must "plan an inquiry-based program," "focus and support inquiries," and "encourage and model the skills of scientific inquiry." Although some science teachers use traditional, direct instruction methods in which students master disconnected facts, students experiencing inquiry-based curricula and instructional methods develop broad understandings, critical reasoning skills, and problem-solving skills. Inquiry learning requires environments and experiences where students can confront new ideas, deepen their understandings, and learn to think logically and critically. Five essential features of this type of classroom are

1. Learners are engaged by scientifically oriented questions. Helping students to change their "why" questions into "how" questions narrows the inquiry into a "testable" question.
2. Learners value evidence, and develop and evaluate explanations that address scientifically oriented questions. Scientific explanations about how the natural world works can be inferred from data that can be validated by other scientists – empirical evidence. Explanations based on myths, personal beliefs, religion, superstition, or authority may be personally useful and socially relevant, but they are not scientific.
3. Learners formulate explanations from evidence. Learners create a set of logical explanations, a conceptual framework, using the collected empirical evidence to address their question.
4. Learners evaluate their explanations in light of alternative explanations, particularly those reflecting scientific understanding. One explanation is selected and alternate explanations rejected through an evaluation process. The best explanations are consistent with evidence.
5. Learners communicate and justify their proposed explanations. Explanations are communicated to interested others for skeptical review and assessment.

The most important variation within the essential features is the degree of teacher versus student self-direction. Teacher direction may be needed to launch an inquiry, support the learner, or focus attention on a particular method or topic. At other times, the student will benefit from developing a personal method of organizing data or reporting to others.

Classroom Implications

In inquiry-based classrooms, teachers support students as active learners as they explore, carefully observe, plan and carry out investigations, communicate through varied methods, propose explanations and solutions, pose thoughtful questions, and critique their science practices. Teachers in inquiry-based classrooms

- Concentrate on collection and use of evidence
- Act as facilitators or guides
- Help students benefit from mistakes
- Model inquiry behaviors and skills
- Use appropriate process vocabulary
- Encourage dialogue among students and the teacher
- Pose thoughtful, open-ended questions and help students do the same
- Provide a rich variety of materials and resources for investigation
- Use raw data and primary sources of scientific information
- Assist students with clear oral and written communication
- Allow students to expand upon previous inquiry activities

Inquiry-based learning need not always be a hands-on experience. Reading, discussion, and research are fruitful techniques for practicing scientific inquiry when scientific questions and evidence-based arguments are used. Similarly, a hands-on, inquiry-based experience can fail to help students learn the abilities and understandings of scientific inquiry if those learning goals are not explicitly addressed.

Teachers should experience scientific inquiry themselves in professional development, where their instructors model the role of teacher as facilitator of learning. Learning how to support student learning through skillful questioning strategies requires ongoing professional development, discussion among peers and personal reflection. Peer coaching and videotaping can be successfully used to improve teachers' questioning skills. Examination of student work can also yield many insights into students' thinking processes and understanding of scientific inquiry.

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What role does teacher questioning play in learning science?

Good questioning requires skill and planning.

Research and Best Practice

Learning is maximized in classes where questions are encouraged, elaboration and explanation are expected, and feedback is frequent. In such classrooms, both large and small group discussions are prevalent, with interaction between teacher and students and among students.

Effective science teachers (those who are highly rated by their students and whose students perform well on both knowledge and inquiry skills assessments) ask many questions of all types during their lessons. Compared to less effective teachers, they pose more questions with higher cognitive demand, and ask more follow-up questions. Their students ask more questions as well. Questions focus on what is important as opposed to what is unusual. Effective teachers also orchestrate productive discussion in classrooms. Students engaged in discussion are able to make sense of ideas, create as well as demonstrate understanding, and reflect on their thinking. Questions can be used as an effective learning tool prior to a learning experience.

Students in high performing and conceptually oriented classrooms are expected to share ideas with others. Striving to explain helps them clarify their own ideas even when their thinking is not totally clear or their understanding is not well formulated. Students who must explain their thinking organize thoughts differently, analyzing strategies by engaging in self-reflection and analysis.

Studies of questioning in typical science classrooms confirm that most questions make minimal demands on student thinking. Low-level questions include yes/no inquiries, guessing, simple recall of fact, formula, or procedure, leading or rhetorical questions, and those answered immediately by the teacher. Answers are often immediately judged right or wrong by the teacher, and discussion moves to the next question. Increasing the wait time between posing a question and expecting an answer, increases the number of responses, student confidence, responses by less able students, and reflective responses.

Classroom Implications

Better teacher questioning practices lead to better learning by all students. The foundation of good questioning is strong content knowledge, which is a critical factor in enabling teachers to understand and respond appropriately to students' questions. In addition, teachers must have a firm understanding of how students learn topics so they can anticipate students' misunderstandings, and plan appropriate questions.

Good questioning requires skill and planning. Strategies to improve questioning techniques include

- Plan questions while preparing lessons. Write out questions to launch a lesson, and possible clarifying questions to use during exploration.
- Choose different questions for varied purposes — clarifying questions, redirecting questions, summarizing questions, extension questions, reflection questions.
- Tape lessons occasionally to monitor levels of questioning.
- Focus questions on searching for student understanding. Remove emphasis from right or wrong answers. Low-level questions do not give a good picture of a student's grasp of a concept.
- Listen carefully to student answers.
- Ask for a paraphrase of what has been said. This improves attentiveness and assesses comprehension.
- Assume that every answer given by a student is meaningful and "correct" to that student. They give insight into the student's mind by illuminating misconceptions and misunderstanding.
- Begin lessons with thought-provoking questions or problems to engage students and lead to new understanding of important content. Provide a variety of tools to assist exploration.
- Provide multiple opportunities for social interaction around science ideas. People construct learning by questioning, discussion, and reflection.
- Allocate time carefully. Make notes on effective amounts of time for each class.
- Increase wait time. An observant teaching partner can assist.
- Model self-questioning by "acting out" thinking when inquiring about a problem: "I wonder what I should do next? Maybe I should try ___."

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How can teachers motivate students to enjoy and want to learn science?

"Children's curiosity and persistence are supported by adults who direct their attention, structure their experiences, support their learning attempts, and regulate the complexity and difficulty levels of information for them."

Bransford, J. D., Brown, A. L., & Cocking, R. R., 1999, p. 100.

Research and Best Practice

Teachers and parents are often frustrated by students' poor attitudes about science and their lack of motivation to exert effort and learn. A school's commitment to educate all learners needs enthusiastic student participation in order to make the vision of success for all a reality. Motivation to learn can be enhanced through teacher behaviors, curriculum, and the culture of the classroom. Highly motivated students identify certain teacher characteristics as contributing to their attitude. These characteristics include being knowledgeable about the subject matter, a capable communicator, committed to student success, creative, and competent.

There is an art to posing inquiry-based science questions in a manner that encourages and supports further investigation, reveals student understandings and misconceptions, and values progress toward explanations consistent with scientific knowledge. There are cultural differences in children's experience with various kinds of questions and interactions with adults. All students can benefit from learning how to learn and recognizing their individual learning styles.

A standards-based curriculum provides information on what students should learn, but teachers make the curriculum accessible to students through their choice of instructional materials, lessons, homework, and types of assessment. An optimal level of difficulty and complexity of learning experiences helps motivate students. Students respond positively to being intellectually challenged: therefore, the curriculum does not need to be watered down for reluctant learners. Students who are not already committed to learning science respond to a curriculum in which the context of what they are learning is explained, giving their activities meaning beyond the classroom.

Positive emotions, such as curiosity, are motivating; and mild anxiety can help focus students' attention. Conversely, intense negative emotions (anxiety, panic, insecurity, and fear of punishment or ridicule) detract from motivation and interfere with learning. If classroom climate values learning above performance, teacher comments rather than grades can motivate further learning. Motivation also can be enhanced by social opportunities – collaboration in designing experiments, peer reviews, and publishing findings.

Classroom Implications

Science teachers know that many students – particularly the youngest – have a drive to solve scientific problems, and an equally great ability to generate new problems through limitless questions. One way to keep that motivation intact is to choose instructional materials that emphasize direct student involvement with natural phenomena. Equally promising is problem-based learning, where the social impact or meaning for the investigation is clear and provides a context for assignments.

Cooperative learning provides a social context that motivates many students; provides support – and reduces anxiety for – language learners; and affords opportunities over time to showcase diverse learning styles and talents. Careful planning of the roles assigned to students in groups, the choices offered, and the kinds of social interactions expected can increase the effectiveness of cooperative learning.

Portfolios of student work help show progress toward subject matter mastery and – when examined carefully by student, teacher, and parent – can motivate a child to keep learning. Unfortunately, grades can have the opposite effect. When specific criteria for grades are discussed in detail before the work begins, however, students are more motivated. Rubrics provide enough detail to model exactly what is expected. Some teachers have students participate in setting the criteria. Constructive teacher feedback can also serve as a powerful motivator of learning.

Students can increase self-motivation and success by learning how to learn. Teachers and parents can help by pointing out the student's strengths and explicitly teaching strategies for overcoming weaknesses. Students should learn to plan, monitor, and revise and reflect on their own learning. Also, some students, believing they lack a "talent" for science, need to be convinced that effort can overcome any (perceived) lack of ability.

Students are motivated by teachers who can explain connections among science disciplines, the nature of science, the history of science and technology, and how science is applied in real life. Professional development in science content must be ongoing. Teachers need to practice turning "Why?" questions into testable ones. Time to read, attend classes, and meet with peers is essential to teacher improvement.

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How does linking instruction with assessment impact student learning?

Research and Best Practice

Classroom assessment is an essential tool for supporting and monitoring student learning of science standards. It should be aligned with instruction in at least three important ways. First, classroom assessment within a unit should reveal to teachers what individuals and groups of students know, understand, and can do with the material they are learning. Ongoing assessments may include informal conversations with and observations of students, open-ended performance tasks that reveal student understandings and misunderstandings, and traditional paper-and-pencil tests such as multiple choice. Teachers should decide what type of ongoing assessments to use based upon learner and instructional needs. It is more effective to have frequent, short assessments using a variety of strategies than infrequent, long assessments.

Ongoing embedded classroom assessment should promote student learning.

Second, ongoing embedded classroom assessment should promote student learning. When solving problems that require the application and integration of knowledge, a student learns not only the skills and reasoning needed to approach novel problems, but also begins to develop deep understanding of new science concepts. For assessment to promote learning, it should be accessible to students (that is, it must use the skills and knowledge that students have already mastered), motivating, and contain valuable science skills and content. This requires teachers to carefully construct, adapt, or design assessments that promote learning. Teachers must facilitate students' working through misconceptions toward the acquisition of new concepts and processes. Teachers should collaborate with their peers to generate quality assessments.

Third, classroom assessment should help students monitor their own learning. When students know what is expected of them, through feedback and grading criteria, they are better able to keep track of their own mastery of the material. Grading should be made clear to students through rubrics that are written at a developmentally appropriate level. When students know what aspects of a skill or concept will be assessed (e.g., written communication of their experimental design), they are more likely to complete assessments to meet the scoring criteria.

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Classroom Implications

National or state standards – what students should know and be able to do – provide the link between instruction and classroom assessment. During the process of planning instruction and assessment, teachers develop achievement targets that are aligned with standards. Appropriate curriculum and instruction will support student progress toward achievement targets as documented by assessments. When aligning instruction and assessment, teachers should consider five interrelated achievement targets. They are

- Knowledge students need to master
- Kinds of investigations and performance tasks students need to be able to design and complete
- Skills students must be able to demonstrate
- Products students must be able to create
- Attitudes toward science the teacher hopes students attain

Knowledge provides the foundation for the other four targets. Science inquiry is necessary for skill demonstration and product development. Positive attitudes toward science result from the amount of success in academic performance.

Constructive teacher feedback that addresses specific qualities of student work enhances learning. At the beginning of a unit of study teachers should pre-assess student knowledge and skills. Based upon the preassessment results, teachers should design an instructional program that promotes successful learning experiences for each student. Embedded assessments within a science unit should blend strategies such as performance-based tasks, informal assessments (e.g., teacher observation and communication with students), journals, and traditional paper-and-pencil tests (e.g., short answer) that mirror day-to-day classroom instruction. Teachers should strive for assessments that ask students to apply concepts to real-world situations. Assessments also need to be fair to all students and accommodate a variety of developmental levels and learning styles.

As teachers examine student work and review assessment data, they should look at what students know and can do in addition to the opportunities that have been provided for students to learn. Student results should guide further instruction and assist students with information for improvement.

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How can a science teacher ensure a safe teaching and learning environment?

"Inherent in many instructional settings including science is the potential for injury and possible litigation. These issues can be avoided or reduced by the proper application of a safety plan."

Position statement on safety and school science instruction. Adopted 2000. National Science Teachers Association. www.nsta.org

Research and Best Practice

High quality science teaching includes interaction with materials through demonstrations, laboratory investigations, and field trips. With increasing emphasis on active, student-centered learning, it is important for science teachers to be as knowledgeable as possible about safety issues and their responsibilities. It is imperative that teachers set a good example by following professional safety guidelines.

Science teachers have three basic legal responsibilities, known as duties. First is the duty of instruction on all foreseeable and reasonable hazards. Teachers should provide adequate instruction on safety procedures and concerns before students conduct laboratory investigations. Teachers also have the duty of supervision, which includes ongoing monitoring of student activities. They should make sure students behave properly in light of any foreseeable dangers. Finally, teachers have the duty to maintain a safe environment for students and faculty.

There are many components of an effective safety program at the classroom level. They include safety checklists; safety rules and guidelines established by national, state, and local regulatory agencies and organizations; procedures for purchasing, storage, and disposal of chemicals, and care and handling of animals and plants; accident guidelines; use and maintenance of protective equipment; and a safe physical layout of the classroom. Science teachers should have frequent updates and training on science safety issues and current rules and regulations. Topics should include how to handle emergency situations and knowledge about legal liabilities.

Administrators and districts have safety responsibilities as well. Students should learn science in a science-equipped classroom that has adequate ventilation. Class size should be appropriately limited. Written procedures should meet or exceed the standards adopted by the Environmental Protection Agency (EPA), the Occupational Safety and Health Administration (OSHA), and/or appropriate state and local agencies regarding use of materials and equipment, management of hazardous materials, and disposal and storage of chemical and biological products. Districts should provide safety and personal protective equipment, appropriate documentation, and necessary annual science teacher training. Teachers should be informed of the nature and limits of liability and tort insurance carried by the district, and of individual student health concerns.

Classroom Implications

Duty of instruction requires that teachers provide students with information prior to investigation that

- Is accurate
- Is appropriate to the situation, setting, and maturity of the students
- Addresses reasonably foreseeable dangers
- Identifies specific risks
- Explains and models proper procedures to be used
- Describes appropriate conduct in the lab

Both students and parents should receive written copies of safety guidelines for the science classroom. Teachers may choose to present this information as a safety contract to be signed by the student, parents, and the teacher.

In responding to the duty of supervision, a teacher must always keep safety foremost in mind. Misbehavior should never be tolerated, and students should always be supervised in the science classroom and elsewhere. Younger students and those with special needs require a greater level of supervision, as do all students during activities with higher levels of potential danger. Safety equipment, such as fire extinguishers, and personal protective equipment, such as eye wash stations and goggles, should always be available and used when appropriate. Food and drink should never be permitted in any space where hazardous chemicals or materials are used.

Duty of maintenance requires that teachers should follow all safety guidelines for proper labeling, storage, and disposal of chemicals. Material Safety Data Sheets (MSDS) should be available in compliance with OSHA and other federal regulations. Teachers should establish and follow safety inspection schedules and operational procedures. They should never use nor ever allow students to use defective equipment. When hazardous conditions exist, teachers should immediately file a written report with appropriate administrators. Districts should provide and require all teachers to attend ongoing science seminars or training on all aspects of safety, including rules, regulations, and legal liabilities. Safety notebooks that are regularly updated for all district science teachers are a useful tool for discussion and professional development.

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How does teacher content knowledge impact instruction?

"One of the most serious questions in science education is what science a teacher needs to know."

National Research Council, 1996, p. 59.

Research and Best Practice

Three of the Science Teaching Standards within the *National Science Education Standards* are: planning an inquiry-based science program, guiding and facilitating learning, and assessing students. The national standards also recommend that teachers have deep understanding of scientific inquiry and the fundamental facts and concepts in major science disciplines; be able to make conceptual connections within and across science disciplines, as well as with other content (e.g., mathematics); and use scientific understanding and ability when addressing personal and societal issues.

A study of the relationship between teacher quality and student achievement indicates that teachers with more content knowledge are better at seeking information from students through questioning and discussions than teachers with less content knowledge. The same research also shows a positive correlation between the number of science courses taken by teachers and the extent to which their students report liking science. Teachers expert in science content notice meaningful patterns of information, are able to apply their knowledge, and can easily retrieve important aspects of their knowledge. In contrast, teachers with superficial science content understanding often emphasize memorization of isolated facts, rely too much on textbooks, are limited in creativity, ask lower-level questions of students, and are unable to help students make connections among concepts.

However, teacher content knowledge alone is not enough to ensure effective teaching. Many studies indicate that teaching strategies used in the classroom also play an important role in improving student achievement. These studies consistently show that the quality of teaching is influenced by a teacher's content background and use of effective pedagogy.

Classroom Implications

Teacher education programs should require laboratory and field-oriented experiences in all of the earth/space, life, and physical sciences. Even if a teacher is intending to become certified in just a single science discipline, physics for example, the value of such preparation lies in the holistic and interdisciplinary understanding of science that it provides. Science teacher preparation course work, from both science departments and education departments, should enable teachers to

- Teach significant earth/space, life, and physical science content to all students
- Explain any science topic in the context of the unifying concepts and processes of science
- Promote student inquiry competencies in a variety of activities such as laboratory investigations, field work, and discussion
- Embed science processes such as investigating natural phenomena, interpreting data, and communicating conclusions into learning activities
- Relate learning science to understanding about technology, personal and social perspectives, historical issues and cultural values
- Coach students in the use of decision-making and valuing procedures in the investigation of scientific societal problems
- Encourage the application of basic mathematics and computer skills to inquiry and analysis
- Model an inquiry approach to learning about natural phenomena
- Make connections across scientific disciplines and other disciplines (e.g., mathematics, social sciences, language arts)

These capabilities are outlined as student expectations for content competency in the *National Science Education Standards.* Certainly they should apply to their teachers as well.

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How does teacher pedagogical knowledge impact instruction?

As teachers' pedagogical content knowledge increases within the context of a strong knowledge of content, their ability to impact student learning also increases.

Research and Best Practice

Pedagogical knowledge means understanding the methods and strategies of teaching. Specific methods or strategies that have been proven to work well in one content area, such as science, are referred to as pedagogical content knowledge. Good pedagogical content knowledge in science is the ability to teach science well.

According to the *National Science Education Standards*, the most direct route to improving science achievement for all students is through better science teaching. However, despite significant changes throughout society over the last half-century, teaching methods in most science classes have remained virtually unchanged. Many science students spend much of their time memorizing facts and definitions.

Student knowledge improves substantially when their teachers have strong content and pedagogical knowledge. Strong teacher content knowledge alone does not change student knowledge. On the other hand, use of effective pedagogical methods without adequate content knowledge does not improve student achievement substantially, and in some cases may actually reinforce student misconceptions.

Three components influence student achievement: teacher characteristics (e.g., educational background, years of experience), professional development (e.g., training to support classroom practices), and classroom practices (e.g., small-group instruction or hands-on learning). The greatest role is played by classroom practices. The most effective practices engage students in higher-order thinking skills and hands-on learning activities. Other proven teaching practices that increase student conceptual understanding, thinking skills, and often attitudes, include use of a learning cycle lesson plan (e.g., exploration, invention, and application), cooperative learning, wait time, graphic organizers (e.g., concept maps), realistic computer simulations or actual observations, clear objectives, and ongoing feedback on student work.

Specific strategies that assist students with learning for deeper understanding encompass generating and testing hypotheses; determining similarities and differences (e.g., comparing, classifying, using metaphors and analogies); summarizing and notetaking; and activating prior knowledge about science concepts. In addition, professional development tailored to increase teacher repertoires of classroom practices, coupled with content knowledge, supports high student academic performance.

Classroom Implications

One teaching method is not better than other methods; however, there are limitations in relying on just one teaching method. Different methods accomplish different goals. Effective science teachers employ a large repertoire of instructional methods, strategies, and models to produce more successful learners. Different methods accomplish different goals for different students. Teachers should carefully select and plan for experiences to provide meaningful science learning opportunities for their increasingly diverse student population. High-quality science teaching

- Includes a deep knowledge of subject matter
- Incorporates inquiry as a primary mode of teaching
- Encourages all students to learn for understanding
- Focuses on the skills of observation, information gathering, sorting, classifying, predicting, and testing
- Fosters healthy skepticism
- Allows for, recognizes, and builds on differences in learning styles, multiple intelligences, and abilities
- Grounds itself in careful alignment of curriculum, assessment, and high standards
- Measures its effectiveness through student performance and achievement
- Builds on real-life situations that apply concepts in new contexts
- Incorporates a variety of technology tools such as computer simulations
- Provides opportunities for discussion and reflection
- Uses ongoing written communications

Contrary to the idea that the ability to teach is innate, specific teaching skills can be acquired through training, mentoring, collaborating with peers, and practice. To change the way they teach, science teachers must have first-hand opportunities to learn in different ways. These varied methods can include inquiry, constructivism, wait time, the learning cycle, graphic organizers, cooperative learning, and science laboratory activities.

Teachers need to observe, practice, and refine high-quality teaching to master the art of teaching science well. As teachers' pedagogical content knowledge increases within the context of a strong knowledge of content, their ability to impact student learning also increases.

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What is the role of professional development in improving teaching in science?

The quality of science teaching depends...on how schools structure teachers' work assignments, teachers' learning opportunities, and the school-level climate of professional inquiry to support student achievement.

Research and Best Practice

The most powerful instrument for change lies at the core of education with teaching itself. The way to foster students' interest and learning in science is through competent teachers who are not only enthusiastic about their subject, but who are also steeped in their disciplines and who have had sustained professional learning opportunities. Professional development plays a pivotal role in enabling standards to transform science teachers' classroom practices.

In the past, professional development meant skill training. Since the current reform effort requires a substantive change in how science is taught and learned, an equally substantive change is needed in professional development practices. The *National Science Education Standards* describe Standards for Professional Development for Teachers of Science in terms of what teachers need to learn and how they need to learn it.

What is required goes beyond skill training to organizational development, which involves not just changes in individual teachers' beliefs and abilities, but also improvements in the capacity of the organization to solve problems and renew itself. Organizational development involves transforming schools into centers of inquiry – that is, centers of continuous learning for students, teachers, and administrators alike. This reform requires a comprehensive, rather than a piecemeal approach to professional and organizational development.

Effective professional development should include three components to nurture continuous improvement: context, process, and content. Context refers to the system or culture where new learnings will be implemented; process addresses how new knowledge and skills will be acquired; and content encompasses skills and knowledge needed for classroom teaching. Professional development requires careful planning that should be guided by a design process. Plans need to encompass what is known about learners and learning, teachers and teaching, the nature of science as a discipline, principles of effective professional development, and knowledge about change and the change process. The needs of teachers are integral to the planning process.

Classroom Implications

Professional development in the context of organizational development means

- Respecting the professional judgment of teachers
- Encouraging teachers to work together to analyze and solve problems at the school and district level, not just at the classroom, team, or department level
- Modifying school policies and governance structures to ensure teacher participation in decisions on professional growth and the mission of the school
- Cultivating a school culture (the norms, values, and beliefs that underlie formal operations and help establish a school's identity) that promotes collaboration, risk-taking, and continuous learning
- Actively seeking evidence on the effects of professional development efforts, particularly the effects on student achievement, and making adjustments in response to the evidence

Teachers and administrators at each school will work together to design and implement a coherent professional development plan based on a vision of overall school improvement. The plan should follow a design process with a major focus on what we know about learning and teaching. Context, process, and content components need to be included in the planning process. One major advantage of this approach is that it involves teachers in the design of their own professional development activities. Such involvement gives teachers the opportunity to think about and discuss their own strengths and weaknesses, the needs of their students, and the direction of the school as a whole.

Ultimately, the quality of science teaching depends not only on the qualifications of the individuals who enter teaching, but also on how schools structure teachers' work assignments, teachers' learning opportunities, and the school-level climate of professional inquiry to support student achievement.

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What are the characteristics of effective professional development for science?

"Much of what constitutes the typical approach to formal teacher professional development is antithetical to what promotes teacher learning."

Bransford, J. D., Brown, A. L., & Cocking, R. R., 1999, p. 240.

Research and Best Practice

Improving teacher quality is the key to increasing student learning. In the past, short episodic pullout training transmitted discrete skills and techniques to teachers who were then expected to deliver content to students. A growing consensus about effective professional development is that it is most powerful when embedded in the daily work life of teachers to create a collaborative culture of inquiry about student understanding. In this environment, teachers learn new content and teaching practices, apply them in the classroom, then reflect on the results.

In this approach to professional development, teacher dialogue about teaching and learning, is guided by

- What state and national standards identify as the most important content and strategies for student learning
- What collected data (e.g., performance assessment, student observation, student interviews, standardized test results) tell about student learning
- What their own inquiries (e.g., action research, study groups) tell them about improved practice

In this way, teachers build professional communities, reduce professional isolation, and remake their professional culture. The most effective schools have strong professional communities, characterized by ongoing collegial and collaborative inquiry into practice. Many U.S. schools are not structured for teachers to learn. However, schools that demonstrate continuing improvement in classroom practice focus on teacher learning within the context of a professional community. Teaching improves in schools that transform themselves into cultures of collegiality, experimentation, and risk-taking. In some districts, professional development schools are providing opportunities for expert, novice, and preservice teachers, university faculty, and teacher leaders to collaboratively study teaching and learning. In this setting, school and university educators work as partners to improve classroom practices.

Classroom Implications

Effective professional development strategies help teachers work collaboratively to reflect on practice within a collegial culture. The five major purposes of professional development for teachers are (1) developing awareness,
(2) building knowledge, (3) translating knowledge into practice, (4) practicing teaching, and (5) reflection. Different strategies address one or more of these different purposes:

- Immersion in science inquiry: engaging in inquiry-based science investigations as learners
- Study groups: engaging in regular collaborative interactions around topics identified by the group to examine new information, reflect on classroom practice, and analyze data
- Case discussions: discussing problems and issues illustrated in written narratives or videotapes of classroom events
- Examining student work: examining students' work to understand their thinking so that appropriate instructional strategies and materials can be identified. (Scoring assessments can lead to the same outcome)
- Action research: examining one's own teaching and students' learning through a classroom research project
- Curriculum implementation: learning, using, and refining specific curriculum materials builds understanding
- Curriculum development and adaptation: creating new instructional materials and strategies or adapting existing ones to better meet the learning needs of students
- Coaching and mentoring: working regularly with another teacher at the same or greater level of expertise to improve teaching and learning
- Lesson study: designing, implementing, testing, and improving one or several lessons over long periods, ranging from several months to a year
- Experience with science research: engaging in authentic research activities in a laboratory, industry, or museum setting

In order to engage in this kind of professional development, teachers need administrator support, time to work with colleagues, and access to resources, such as research and outside expertise. For teacher learning (and, therefore, student learning) to become a priority, the structure of schools and the policies affecting them must change.

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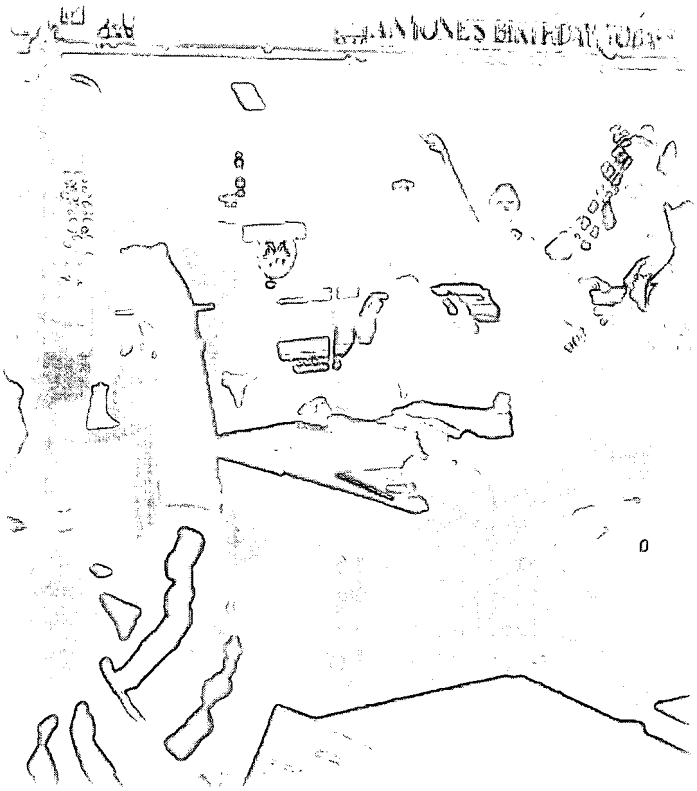

Assessment In Science

Assessment is a complex, systematic procedure for collecting and interpreting data. In education, assessment is the primary mechanism for feedback to students and teachers – as well as to parents, the school district, and the community. The *National Science Education Standards* (*NSES*) recommends the use of multiple assessment methods. Since assessments communicate expectations, providing an operational definition of what is important, the *NSES* promotes the inclusion of authentic assessments, or "exercises that closely approximate the intended outcomes of science education" (p.78).

The *NSES* standards for Assessment in Science Education also recommend measuring both students' achievement and their opportunities to learn. Interpreted together, this information assists educators and the community at large in ensuring that all students can achieve to their potentials. Opportunity-to-learn measures are important in interpreting both high-stakes individual assessments and international achievement comparisons.

What role does assessment play in science teaching and learning?

Research and Best Practice

Assessment has traditionally been used to evaluate student achievement and content area programs. New approaches to science teaching have expanded the role of assessment to include monitoring student progress and making instructional decisions. Research and professional science organizations endorse the use of multiple and varied assessment methods, such as performance-based assessments, teacher observations, interviews, student projects, portfolios, and presentations. Such alternate forms of assessment generate the information a teacher needs to determine what students are thinking, how they are reasoning, and what the next instructional steps should be.

Student learning improves when assessment is a regular part of classroom practice.

Student learning improves when assessment is a regular part of classroom practice. Classroom assessment at the start of a unit of study will help to diagnose what students already know and can do related to the unit. Teachers then can base instructional decisions upon individual and class needs. As teachers give a variety of assessments throughout a unit of study, they should give feedback to students on improving their work. The results of these assessments also guide further instruction.

National and state assessments have an influence on what teachers, administrators, and parents value in the classroom. Because of this, adjustments are made to teaching and curricula that reflect the format and characteristics of these assessments, even though the changes (e.g., eliminating science laboratory activities) are not always consistent with recommendations from professional science education organizations. These standardized assessments tend to favor multiple choice formats which give the impression there is always one right answer, a stand that also conflicts with the principles of science education organizations. Some assessments are being used for purposes for which they were not designed and the data collected is being misapplied or misunderstood.

Classroom Implications

Assessment helps teachers plan curricula, guide daily instruction, and provide feedback on student learning. A coherent curriculum requires that assessments reflect what is addressed in the classroom. Although selected-response assessments (multiple choice, true-false, matching) usually assess only knowledge and factual information, well-constructed items can also assess complex understanding. In constructed-response assessments, students demonstrate their learning by choosing how to answer the question. Performance tasks integrate concepts, skills, facts, reasoning, and inquiry, but require time to implement and score. Observations, checklists, interviews, and portfolios allow students to demonstrate their achievement and progress, especially when students' reading and writing abilities may influence assessment results. Standardized, norm-referenced tests can suggest students' relative strengths and weaknesses across different content strands. Teachers should choose assessments to integrate with instruction to improve student learning.

Rubrics should be used to consistently describe levels of achievement for the skills, knowledge, and understandings being assessed. Communicating expectations with students prior to tasks can promote quality work on the assessment. Analyzing student work can help teachers see the depth of students' thinking, as well as pinpoint sources of error or misunderstanding. It is important to devote professional development time and resources to help teachers learn how to analyze and respond to both typical and unconventional student work. In analyzing assessment, three questions should guide future decisions about teaching and learning:

- What are the student results?
- Why did these results occur?
- How do we improve the results?

Teachers need to become more proficient in thoughtfully interpreting data from the various reference models of assessments (norm-referenced, criterion-referenced, and growth continuum). Learning to use evidence from multiple sources of assessment data can yield a more accurate picture of what students know and are able to do. The data can also help educators make decisions as to whether there is curricular alignment or if delivery of the content needs to be modified.

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How can the use of varied assessments provide important evidence of learning?

The use of multiple means of assessment allows students to diversify thinking and response patterns.

Research and Best Practice

Because each assessment strategy has strengths and weaknesses, using a wide variety of classroom assessments gives a better picture of student learning than any individual approach could alone. Assessments not only measure current achievement levels of students but should also monitor and report on student achievement over time. Traditionally paper-and-pencil measures such as multiple choice, true-false, and short answer, were used as standardized measures and classroom assessment. These traditional assessments still play a role, but need to be expanded to a wide variety of alternative assessments that encompass other sources of evidence about what students can do and what they are thinking. Alternative assessments encompass options such as teacher observations, portfolios, inquiry-based investigations, interviews, journals, performance tasks using manipulatives, use of drawings and pictures, and building models. Use of alternative assessments can demonstrate how students apply knowledge. Multiple sources of evidence yield a more comprehensive ongoing picture of student learning and academic progress, facilitate the exchange of information between teacher and students, and can be communicated readily to other members of the school community.

Curriculum, instruction, and assessment are closely linked. Good teachers deliberately use both formal and informal assessment of student growth to more closely align instruction with developing student understanding. Use of multiple assessments of student learning allow teachers to refine their knowledge regarding content that is important for students to learn, pedagogical techniques that enhance learning, and how specifically to teach science concepts and inquiry-based strategies.

Students assume more responsibility for their input into the classroom discourse and become more reflective. They learn to focus on listening more productively, on communicating more clearly, and on investigating more deeply. Using specific results to inform actions, students gain confidence in tackling science problems and in analyzing strategies and solutions. Multiple assessment measures, coupled with students' and teachers' awareness of the importance of assessment to teaching and learning for understanding, can help foster a learning environment centered on continual growth. Ongoing feedback on student assessments with opportunities to revise work helps students gain a deeper understanding.

Classroom Implications

Science teachers need to discuss the importance of continuous assessment with students. Scoring criteria and models of exemplary work need to be given to students before they begin their tasks. When students and teachers collaboratively establish assessment as a tool to inform classroom progress, finding a variety of appropriate measures becomes an important component of the instructional process. This includes making appropriate accommodations for students with special learning needs.

Effective teachers use questioning, classroom observations, interviews, and conferences to facilitate instruction and to inform decision-making. Scientific questioning helps students scaffold knowledge, focus thinking, and dig deeper into understandings. Observations framed around students' grasp of scientific concepts, their dispositions toward learning, their communication abilities, and their group work contributions help the teacher identify appropriate instructional strategies. Interviews yield individual insights into a problem, a way of thinking, an orientation to science inquiry, and a uniqueness of approach. Conferencing allows students and teachers to reflect together on knowledge gained, current disposition toward science, and goals to pursue.

Individual self-evaluation through reflection pieces, a science autobiography, scientific goal-setting, individual daily evaluations, chronicling of "ah-ha's," record keeping, journaling, and writing in science personalizes the activity for the student. Through writing, students learn to organize, to convey, to question, to conclude, to defend, all scientific thinking processes. Conversation with peers augments learning.

The use of multiple means of assessment allows students to diversify thinking and response patterns. Unique assessments congruent with conceptual understanding such as use of real world problems, computer-based assessment of higher order understandings and processes, critical evaluation of scientific logic, and investigation of structured inquiry tasks are stretching thinking about meaningful science assessment. Scoring methods such as rubrics developed jointly by teachers and students can help focus learning on understanding, conceptual development and science process skills. A wide variety of assessments can facilitate classroom focus on standards-based science experiences. Therefore, teachers need to increase their repertoire of assessment strategies. Ongoing professional development in which teachers examine a variety of student work is a critical part of assessment.

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How is student inquiry assessed in the classroom?

Because of the nature of inquiry, performance tasks as well as authentic tasks are a natural fit.

Research and Best Practice

The *National Science Education Standards* suggests that "assessments provide an operational definition of standards, in that they define in measurable terms what teachers should teach and students should learn." (pp. 5-6) In regard to inquiry, assessments need to measure the progress of student achievement in the areas of learning science (understanding content), learning to do science (ability to do scientific inquiry), and learning about science (understanding scientific inquiry).

Designing a learning experience for inquiry should involve three questions. (1) What should students learn– the specific learning goal? (2) What teaching strategies will provide opportunities for students to learn? (3) What assessment strategies will provide the best evidence to ensure that students have met the learning goal? When these three pieces are aligned, the students' opportunity to learn increases. In inquiry-based classrooms students monitor progress, both their own and that of the class. Students need to understand the criteria used to evaluate their performance.

As students engage in inquiry-based activities, the teacher can collect evidence about the students' ideas and skills which informs future decisions about further learning. This is an example of formative assessment. Through formative assessment, the teacher determines what understanding of scientific ideas and process skills students have developed to next decide further inquiry lessons. The teacher gathers information about learning in an ongoing way, factoring the students' developmental abilities into the selection of inquiry-based activities.

Methods of gathering evidence of student learning include observing students engaged in inquiry, asking probing questions, looking closely at evidence from class work, and giving special tasks to address student needs. Assessment can include a wide variety of options that are generally performance-based, which may be a product, performance, or process. Some examples are written investigations, research reports, portfolios, journals, laboratory notebooks, oral presentations, writing and presenting a play, videotape productions, projects, models, teaching a lesson to others, and conducting an interview.

Classroom Implications

Inquiry is integral to science learning; therefore, it must be assessed frequently. Ongoing formative assessments help pace instruction and gauge opportunities students have for learning. Achievement data should not only measure student performance but should also inform instruction. Students have a central role in the assessment process. They need to share the teacher's goals for learning and understand learning expectations. Students should be involved in setting criteria to evaluate their work. In addition, students need to be trained in self-assessment and what is needed to achieve success.

When teachers know what they want students to demonstrate, they can better help students learn. Assessing understanding of subject matter could involve an investigation that would measure student understanding of a science concept. Assessing abilities necessary to do scientific inquiry may involve examining laboratory notebooks to evaluate a student's ability to design a controlled experiment. Assessing understanding of scientific inquiry could involve selected response items such as a multiple-choice test in which students identify whether or not explanations are based on empirical evidence.

Teachers can use a variety of strategies to assist with gathering ongoing information about student learning on inquiry-based tasks. These include

- Observing students as they work using checklists as guidelines for observation
- Asking probing questions to determine student thinking
- Evaluating student products (e.g., written explanations, pictures, portfolio entries, models, graphic organizers) that include student reasoning
- Providing thoughtful feedback that includes advice for improvement of work
- Listening to students' verbal explanations which includes "wait time" that gives students time to think before responding
- Providing hands-on or written tasks that allow students to use inquiry skills where they are required to speak or write

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What do national/international assessments say about teaching and learning science?

U.S. science curriculum has a serious lack of focus, coherence, and rigor.

Research and Best Practice

Conclusions from the Third International Mathematics and Science Study (TIMSS and TIMSS-R) and the National Assessment of Educational Progress (NAEP) discuss U. S. curricula, teaching, and learning. TIMSS results show major differences between student achievement in the U.S. and in other countries. Achievement by U.S. 9 year olds, mainly grade 4, was exceeded by students in only one TIMSS country. At age 13, mostly grade 8, U.S. students performed only slightly above the international average. Grade 12 U.S. students outperformed students from only two countries on science general knowledge. NAEP science achievement data indicate U.S. students perform unacceptably at all grades. Performing at proficient or higher levels were 29 percent of students at grades 4 and 8, and 21 percent at grade 12, with differences across states and regions.

TIMSS results show that curriculum and teacher preparation matter. Across content strands, generally U.S. students did best at both grade 4 and grade 8 in earth science, specifically "earth processes," and also in life sciences. The worst content achievement for both grade levels was in physical science. This reflects the general tendency among elementary and middle school teachers to focus more instruction on earth and life sciences. Students' low performance on measurement in mathematics may also have impacted science performance, since lab experiences require measurement. In Minnesota, grade 8 students performed well on TIMSS, perhaps because they experience a more coherent curriculum (all grade 7 students have life science; all grade 8 students have earth science) and focus on fewer topics. Their teachers favor hands-on, laboratory-based instruction. Also, 97 percent of Minnesota science teachers majored in science or science education, which is much higher than the national average.

U.S. science curriculum has a serious lack of focus, coherence, and rigor. U.S. teachers cover many more topics each year than elsewhere. On the average, U.S. grade 8 students cover about 65 topics, while other countries cover about 25 topics in more depth. Many U.S. textbooks fragment the science curriculum, addressing a "laundry list" of topics rather than overarching concepts. Teachers with limited science backgrounds often cannot help students make logical connections among content fragments. Student performance on NAEP was higher when teachers placed a heavy emphasis on understanding key concepts (grades 4 and 8), planned frequent hands-on activities or investigations (grade 8), provided opportunities for students to develop laboratory skills or techniques (grade 8), and talked about science with their students (grade 12).

Classroom Implications

Because states are responsible for their education systems, no one entity directs science programs in the U.S. The result is the splintered vision of science education reflected in TIMSS and TIMSS-R scores. To remedy this situation, science educators should use the *NSES* and *Benchmarks* to focus curricula on powerful central concepts and skills. K–12 alignment of curricula with standards is crucial. All K–12 science content strands should be addressed in more depth, while paring down the number of topics covered each year. Curriculum materials should be carefully selected for their clear focus, coherence, and intellectual rigor, and there should be less reliance on textbooks as guides to instruction.

Lessons should be designed to use effective instructional strategies and to connect the big ideas or key concepts of science. Achievement is increased when students have frequent opportunities to conduct hands-on activities and investigations, with ongoing opportunities to develop laboratory skills and techniques. Encouragement from teachers, counselors, and parents increases the likelihood that students will continue their study of science throughout high school.

International comparisons indicate that the most powerful instrument for change in student performance is improved teaching. High quality teaching

- Requires a deep knowledge of the science being taught, as well as an understanding of what is most important to learn and what is most difficult to understand
- Engages students not only in the factual aspects of science, but also more meaningful conceptual and problem-solving aspects
- Involves the process of inquiry so students learn and apply the lesson content, so students experience what and how to learn
- Insists all students learn at high levels
- Demands high quality professional development opportunities to keep teachers current in content, pedagogy, and assessment
- Includes time to share with colleagues, which is critical to developing a learning community and professionalism among teachers

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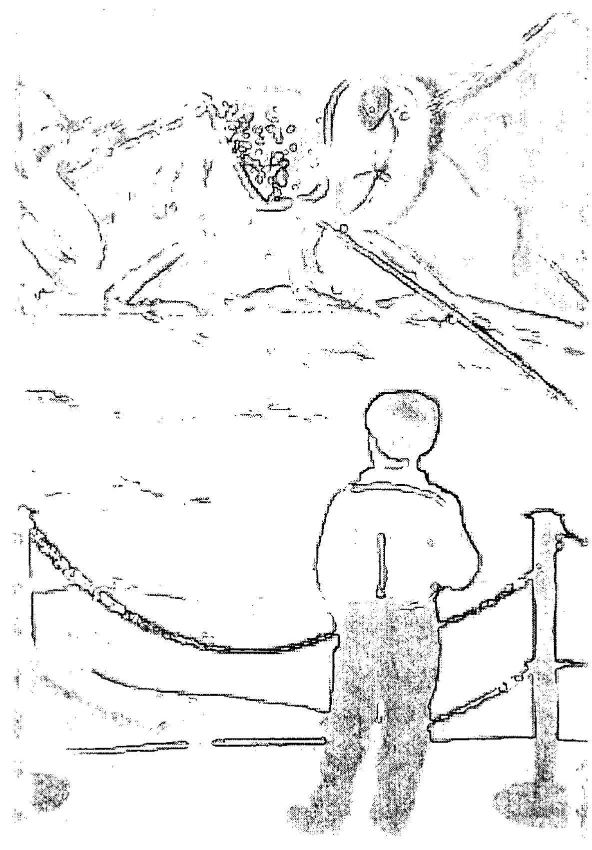

Science Curriculum

Science is constructed of facts, as a house is of stones. But a collection of facts is no more a science than a heap of stones is a house.

Henri Poincaré

National science education standards – the *National Science Education Standards* (*NSES*) and *Benchmarks for Science Literacy* – define the content of instruction, outlining what every student should know and be able to do. It is the district curriculum, however, that describes how that content is organized. In addition, curriculum defines the emphases and perspectives placed on the content, creating a map for educators to use in designing classroom experiences for students.

Recognizing that the intent of content standards is to establish standardized goals for all students, teachers must make curriculum decisions that accommodate a wide variety of learning styles, backgrounds, and interests. When educators use multiple means for addressing each standard, all learners have an opportunity to access common content.

What does it mean to have a standards-based curriculum in science?

"Piecemeal changes are unlikely to lead to significant and lasting curriculum reform. What is needed is a coordinated K–12 plan that guides the curriculum-building process."

American Association for the Advancement of Science, Project 2061, 1993, p. 381.

Research and Best Practice

Standards are goals specifying what students should know and be able to do at certain milestones in their education. A standards-based curriculum specifies how students and teachers will meet those goals – the specific concepts, order, and sometimes the instructional materials to be used. Voluntary national standards for science education were developed by the National Research Council, on behalf of the National Science Teachers Association and several other organizations, and the American Association for the Advancement of Science's Project 2061. The *National Science Education Standards* (1996) and the *Benchmarks for Science Literacy* (1993) were their respective publications. Both documents define what students should know and be able to do to ensure high school graduates become scientifically literate adults. Another national project, The New Standards Project's *Performance Standards for Elementary, Middle,* and *High School,* defines performance standards that specify "how good is good enough," and how students can demonstrate their understanding.

National standards were developed through extensive consensus-building processes involving teachers, school administrators, science education researchers, and scientists. National standards do not, however, prescribe a single approach to teaching science. Local schools determine the way the science content is organized, emphasized, and taught. As of 2000, 49 states had or were adopting state standards, guides, or frameworks for science education, and most had begun to align these expectations with statewide student assessments. Some of these documents are very specific, offering learning goals for each grade or course; others are more general, with milestones for spans such as grades K-3, 4-6, 7-8, and graduation. The degree of alignment between standards and tests is currently being assessed on criteria such as concurrence of content, depth, and breadth of knowledge required, and balance of representation and emphasis.

The translation of standards into classroom activities is a complex undertaking, requiring content to be taught in increasing levels of complexity from kindergarten to grade 12, and yielding a complete program covering all standards. The curricula often exemplify the criticism leveled against American curriculum by TIMSS research. This curriculum study assessed the U.S. science curriculum as being "a mile wide and an inch deep" in comparison to other countries where students performed well on achievement tests yet studied far fewer topics.

Classroom Implications

Teachers provide the interface between standards and students, by designing learning experiences, selecting instructional materials, and assessing student progress. Not only must teachers make long-term plans to "cover" all the standards, but they are also responsible for creating daily lessons that develop student understanding while accommodating diverse needs. The teacher does not do this in isolation, for what students have learned in the previous years and what preparation they need for future classes must also be taken into consideration.

Some strategies for addressing standards include these changing emphases taken from the *National Science Education Standards*:

Less Emphasis On:	***More Emphasis On:***
Knowing scientific facts and information	Understanding scientific concepts and developing abilities of inquiry
Studying subject matter disciplines (physical, life, earth sciences) for their own sake	Learning subject matter disciplines in the context of inquiry, technology, science in personal and social perspectives, and history and nature of science
Separating science knowledge and science process	Integrating all aspects of science content
Covering many science topics	Studying a few fundamental science concepts
Implementing inquiry as a set of processes	Implementing inquiry as instructional strategies, abilities, and ideas to be learned

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How do we determine what students should know and be able to do in science?

In a standards-based curriculum, teachers design learning experiences to enable all their students to reach the level of understanding or skill described by applicable standards.

Research and Best Practice

What knowledge and skills should a scientifically literate high school graduate have? Scientists, teachers, and education researchers answered this question, and received reactions and comments from thousands of their colleagues during the production of the *National Science Education Standards* (*NSES*) and the *Benchmarks for Science Literacy*. Both documents recommend essentially the same content and principles. The *NSES* organizes science content into seven areas: Scientific Inquiry, Life Science, Physical Science, Earth and Space Science, Science and Technology, Science in Personal and Social Perspectives, History and Nature of Science, and Unifying Concepts and Processes. This organization is based on a combination of factors – including cognitive development theory, the classroom experience of teachers, and the organization of schools – and is not necessarily a recommendation of how the curriculum that is delivered to students should be organized.

National standards describe what all students should achieve by the time they reach three or four milestones between kindergarten and 12th grade. These examples from the *NSES* illustrate the milestones for the development of a life science concept:

> **Grades K-4:** All animals depend on plants. Some animals eat plants for food. Other animals eat animals that eat the plants. (p. 129)
> **Grades 5-8:** For ecosystems, the major source of energy is sunlight. Energy entering ecosystems as sunlight is transferred by producers into chemical energy through photosynthesis. That energy then passes from organism to organism in food webs. (p. 158)
> **Grades 9-12:** Energy flows through ecosystems in one direction, from photosynthetic organisms to herbivores, to carnivores and decomposers. (p. 186)

States and districts, influenced by national standards, define their own specific and measurable standards to guide instructional materials selection, test designs, teacher accountability measures, and graduation requirements. For example, the *Texas Essential Knowledge and Skills*, grade 6, concept 6.8, requires that:

> *"The student knows that complex interactions occur between matter and energy. The student is expected to: (A) define matter and energy; (B) explain and illustrate the interactions between matter and energy in the water cycle and in the decay of biomass such as in a compost bin; and (C) describe energy flow in living systems including food chains and food webs."*

Classroom Implications

In a standards-based curriculum, teachers design learning experiences to enable all their students to reach the level of understanding or skill described by applicable standards. Given the diverse backgrounds and interests of students in any classroom, teachers are challenged to present the content in an engaging and accessible manner and to make frequent assessments of the students' understanding.

In designing optimal learning experiences, especially given the amount of material to be covered in a relatively short amount of time, teachers should strive to use problems or questions that integrate several standards, provide opportunities for student investigation, and provide assessment opportunities that do not interrupt the learning process.

Studying standards for student achievement is a critical element in the education of teachers, integrating the need for a solid understanding of science content with experience in an array of instructional strategies specific to science education. Ongoing professional development in both content and pedagogy is best done in connection with classroom practice and in collaboration with other teachers. In this way, teachers can practice how to determine what a student knows – using actual student work and interviews – and share ideas on providing instruction that will enable students to achieve the standards. Scientists can often be of help in providing content-rich professional development and giving updates on new information and applications.

Research on how children learn has brought to light common misconceptions in several science content areas. These incomplete or incorrect understandings make sense to children and can be difficult to overcome and replace with a scientifically correct explanation. Telling or showing rarely changes the student's misconception. The best solution is an interaction between the student and a phenomenon or experimental result that directly challenges inaccurate thinking. A classroom environment in which students explain their thinking and are challenged to provide evidence for their explanations also helps students produce sound conclusions.

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What is curriculum coherence and articulation?

A well-articulated, coherent curriculum program not only is designed to take advantage of important previous knowledge but to have multiple entry points.

Research and Best Practice

The *National Science Education Standards* defines curriculum as the content of instruction and "the structure, organization, balance, and means of presentation of the content in the classroom" (p. 22) extended over time (at least a few years). The *NSES* Science Education Program Standards stress the importance of coherence and articulation in the K–12 curriculum program.

A coherent program is one in which ideas and skills connect and build on one another over time. This means they are clearly described; they include some indication of the level of performance expected of the students; and they are connected in a logical progression. The connectedness and sound development of ideas and skills over the years of schooling in a coherent program is often compared to the progression of a good story. Students become aware of and understand the connections between ideas as the story develops over days, months, and years.

Articulation describes the relationships among various elements in a curriculum. Articulation ensures that there are connections between lessons, units, courses, and grade levels, and that the connections make increasingly rigorous development of ideas possible. Content must be presented to students at a developmentally appropriate time. A well-articulated curriculum challenges students to learn increasingly more sophisticated scientific ideas as they continue their studies. Examining curricula across the entire 13-year instructional span for coherence and articulation defined through standards in use by local school districts is an important way to improve the quality of education.

Project 2061 defines a coherent, articulated K–12 program. In *Science for All Americans*, a common core of learning in science, mathematics, and technology was identified. These core studies include connections among those disciplines. Project 2061 *Benchmarks* further specifies what students should know and be able to do by certain grade levels. The *Atlas of Science Literacy* is a companion document that shows connections among the benchmarks through maps.

TIMSS research shows that most science curricula in the U.S. lack coherence and focus. Comparing U.S. textbooks and curriculum guides with those of other countries shows U.S. texts contain considerably more topics. Covering so many topics results in instruction that yields disjointed rather than coherent learning. This does not allow students to develop deep understanding of the topics covered.

Classroom Implications

Several common practices contribute to lack of coherence and articulation in curriculum. These include

- Emphasis on mastery, using reteaching and repetition
- Use of rote memorization
- Reliance on textbooks that emphasize content "coverage"
- Overly flexible, modular curriculum design
- Lack of district attention to curriculum program development

To achieve coherence and articulation, a curriculum program must

- Focus on the important concepts and skills that are critical to the understanding of important phenomena and relationships that can be developed over several age levels
- Help students develop an understanding of these concepts and skills over several years in ways that are logical and that reflect intellectual readiness
- Establish explicitly the connections among the concepts and skills in ways that allow students to understand both ideas and the connections among them
- Assess and diagnose what students understand to determine the next steps in instruction

A coherent curriculum will typically contain fewer topics, although the topics will be richer and lead to greater depth and persistence of understanding. Content must be presented to students at an age when they have a readiness for it, are capable of understanding it, and can see the relationships among ideas. A well-articulated, coherent curriculum program not only is designed to take advantage of important previous knowledge but to have multiple entry points to allow students who may have gaps in their previous knowledge to participate and learn rigorous content.

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What is the importance of reading and writing in the science curriculum?

Many of the process skills needed for science inquiry are similar to reading skills, and when taught together reinforce each other.

Research and Best Practice

Reading, writing, and science are, or should be, inseparable. Many of the process skills needed for science inquiry are similar to reading skills, and when taught together reinforce each other. Examples of skills in common are predicting, inferring, communicating, comparing and contrasting, and recognizing cause and effect relationships. In language as well as science learning, students analyze, interpret and communicate ideas. These are skills needed to evaluate sources of information and the validity of the information itself, a key factor for scientifically literate citizens. *Becoming a Nation of Readers* suggests that the most logical place for instruction in most reading and thinking strategies is in the content areas rather than in separate lessons about reading.

Students' comprehension of text improves when they have had hands-on experiences with a science concept. Prior knowledge, which is developed and enhanced through science inquiries, is the strongest predictor of student ability to make inferences from text. In a four-year study of elementary students who participated in an active, inquiry-based science program, a direct correlation was shown between higher language test scores and years of participation in the science program.

Writing skills are important to science learning. Students must organize and communicate their observations and data, argue logically, and structure coherent conclusions. Science journals and reports are natural vehicles for increasing writing competence.

Science content has been found to be particularly effective for engaging language learners. Inquiry-based science instruction has been shown to increase vocabulary, not only that directly related to the science content but fluency as measured on standard language tests. One study showed up to four months language growth as a result of a five-week summer elementary science academy. Success serves as a motivator, too, stimulating reading, writing, and oral communication to pursue science inquiry in greater depth.

Classroom Implications

Motivating and engaging students to speak, ask questions, learn new vocabulary, and write down their thoughts comes easily when they are curious, exploring and engaged in science inquiry. Integrating literacy activities within the teaching of science helps clarify content concepts and can make science more meaningful and interesting to the student. Teachers can use a wide variety of literature, including trade books, texts, and fiction. Non-fiction trade books often cover a topic in great detail and use extensive illustrations. Fiction works successfully with young learners by embedding cognitive learning in imaginative stories. The National Science Teachers Association provides annual lists of outstanding new literature and multimedia materials, and teacher guides for science instructional materials often provide lists of relevant books.

Asking students to record data and conclusions in a science journal or to articulate and defend their views about science-related issues provides excellent opportunities for students to clarify their thinking and develop communications skills. Other examples of integrating writing in the science class are recording and describing observations, developing class books on science topics, creative writing on a science topic, or writing persuasive letters on an environmental issue. In middle and high schools, teachers can plan lessons and discuss progress in multidisciplinary teams in order to meet curriculum goals in science and language (as well as mathematics and social science).

For language learners, instruction in science can be enhanced by the use of hands-on materials. Interacting with materials and phenomena enables language learners to ask and answer questions of the materials themselves and use the materials as visual aids in conversation with the teacher and peers. Visual and auditory clues should be plentiful—charts with pictures of materials and key procedures, for example. Teachers should select vocabulary carefully, repeat key words often, refer to charts with the written words, and avoid the use of synonyms. Work in pairs or small groups makes native language support by peers or instructional aids more feasible.

For all students, science teachers can help students increase their comprehension of science texts by activating their prior knowledge through brainstorming, discussing the topic, asking questions, and providing analogies. Specific attention to vocabulary is often necessary to enable comprehension of science texts. Teachers should introduce new vocabulary and use a graphic organizer, concept or semantic map, or collaborative peer study techniques to develop understanding of new words.

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What are the most important considerations in selecting instructional materials?

Given the relationship of the quality of instructional materials to student achievement, it is important to pay sufficient attention to the selection of quality of materials.

Research and Best Practice

Instructional materials for K–12 school science include textbooks, laboratory manuals, kits, software, CDs, trade books and other multimedia materials. They are a primary source of classroom science learning and also play a profound role in the education of teachers, since professional development is often structured around these materials. The process used to select science materials is critical to providing students and teachers with a solid foundation for improving achievement.

Key steps in the process of selecting instructional materials for science education are: establishing a review/selection committee; determining selection criteria; selecting an evaluation instrument; and evaluating and selecting materials. The process may be done at the district, school, department, or even the classroom level. Most decisions must be ratified by an administrator or school board. Many states review materials and restrict districts and schools to choosing among approved materials.

In a school or district with science standards in place, the most important selection criterion is that the instructional materials develop the student understanding called for in the standards. Quality instructional materials will enhance student understanding; promote students' active involvement; have high expectations for all students, with guidance for teaching diverse learners; incorporate scientific inquiry; use an appropriate learning sequence; include assessment instruments and methods; and reflect current research in science education. Reviewers familiar with the discipline and the standards must carefully study both content and instruction. When standards exist, the relevant content must be present or the materials should not be used.

Given the relationship of quality of instructional materials to student achievement, it is important to pay sufficient attention to the selection of quality materials. The capacity to recognize high-quality materials can be developed through professional development in science content, research-based teaching methods, and learning theory. Sufficient time and resources should be provided for the selection process. Professional development specific to the instructional materials is needed for optimal use and often takes as long as three years for teachers to master. Finally, the process and the selections themselves should be evaluated. Data from evaluating the entire selection process can improve the next cycle.

Classroom Implications

Since many teachers base their lesson plans on the materials provided, the science content of the material should match curriculum standards. The more closely instructional materials adhere to the goals of state and national standards, the more likely students are to succeed in achieving those goals. It is also important to check the content of the materials for accuracy, asking scientists to assist in this review if possible.

The organization of science materials and programs should include cohesive units, multi-day lessons, and tasks that allow students time to explore and investigate in-depth science ideas. Materials should develop understanding and abilities in science inquiry, and should emphasize connections within and among curriculum areas such as language arts, mathematics, history, or art. Suggestions for enriched or advanced work are helpful.

Materials should give students opportunities to be active learners through an investigative, problem-solving approach that engages them in the use of the science process skills. Materials should ask students to communicate orally and in writing, both with one another and with the teacher. Technology and manipulatives should help students explore scientific ideas, analyze and interpret data, calculate numerical results, and solve problems. Students should reflect on and evaluate their work.

Instructional materials should provide suggestions for scientific investigations. The suggestions should elicit, engage, and challenge students' thinking, and suggest a variety of methods that give all students an opportunity to learn. In-depth content resources can update or enhance the teacher's understanding.

Student assessment should be integrated into the instructional program, using activities similar to learning activities. The materials should use multiple means of assessment, and suggest ways to assess students individually or in small groups — through observations, oral and written work, student demonstrations or presentations, and student self-assessment. Conceptual understandings and procedural knowledge should be frequently assessed through tasks that ask students to apply information about a given concept in novel situations.

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In what ways can integrating curriculum enhance learning?

If the goal is to produce scientifically literate citizens who can apply scientific thinking in real-life problem-solving, then subject integration is essential.

Research and Best Practice

In real life, learning experiences are not separated into academic disciplines or subject areas. A student's classroom experiences should mirror this. Interconnections among the disciplines, when emphasized at all grade levels, will support learning by making the science curriculum more meaningful.

Brain research has shown that long-term memory, or true learning, depends upon information that makes sense and has meaning. Subject integration helps a student make sense and understand the meaning of new information. Without these connections, students' learning experiences would add up to a collection of miscellaneous topics and unrelated facts. In 1938, John Dewey warned that isolation in all forms is to be avoided and we should strive for connectedness. *Benchmarks for Science Literacy* states that interconnected knowledge should be designed to "see the relationships among science, mathematics, and technology and between them and other human endeavors" (p. 320).

If the goal is to produce scientifically literate citizens who can apply scientific thinking in real-life problem-solving, then subject integration is essential. Problem-based learning, using real-life problems, serves as a powerful motivational tool. When connections are extended across curriculum areas, they establish a mental framework that can be recalled for future problem-solving. This approach helps students see commonalities among diverse topics and reinforces understanding and meaning for future applications. Students can apply their newly gained knowledge to questions they have about why things happen in their world and discuss social implications.

The integration of subject areas often reveals an interdependency among the disciplines. For example, it would be impossible to analyze the results of a science experiment without understanding the mathematics needed for data analysis. Integrating subject areas also increases the chances of stimulating student motivation by connecting to an area of interest. An example of this may be connecting physics with physical education or sports, mathematics with geography, or botany and art.

Classroom Implications

There are many models for integrating curriculum in the classroom. Curriculum integration may be designed and implemented by an individual classroom teacher or created by a collaborative, team effort. Integrated or thematic units may be taught individually or by a multidisciplinary team of teachers, coordinating topics among otherwise separate departments. School culture often determines the most practical method for subject integration.

Science can be effectively integrated at all grade levels with mathematics, language arts, social studies, physical education, and fine arts, among others. Language arts (reading, writing, and communication) should be a strong component of all the disciplines. Mathematics and science are natural partners, sharing similar goals of building process and problem-solving skills. Science provides real-life situations, problems, and experimental data to which students can apply the tools of mathematics. For example, analysis of experimental results often requires tables, charts, and graphing; probability and statistics are used in studies of genetics, populations, and ecology; and measurements of mass, volume, distance, and time are needed for most science explorations.

There are many avenues of integration between science and social studies. Some historical events revolve around great advances in science, and a study of important scientific ideas helps students contextualize the concepts of science and see how ideas change over time. Both societal and scientific perspectives can provide learning opportunities.

The challenges to subject integration are lack of imagination, inadequate teacher training, hindrances to teacher collaboration, and insufficient materials. However, the benefits to the learning process should spur teachers beyond these limitations to develop quality, integrated curriculum.

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How does instruction integrated among science disciplines affect learners?

The natural world is not segmented into separate disciplines.

Research and Best Practice

Science is a way of thinking about and studying the world. Scientists have often specialized in studying a particular portion of nature, perhaps its chemicals or its weather or its plants. Science as an academic course of study has become separated into disciplines – life science, physical science, earth and space science – usually taught as separate courses.

The standards define what students should know and be able to do in all disciplines of science. International test results (TIMSS) show that our students are not meeting these standards with the traditional science curriculum.

An integrated science curriculum or course combines many facets of the science content area. It may include the traditional three divisions of earth and space, life science, and physical sciences (including chemistry and physics). It may also include science processes, the history and nature of science, science in personal and social perspectives, and science and technology. Cross-disciplinary concepts may be embedded in each lesson. Coherent connections are made between concepts from different science disciplines. Research on the brain indicates that it searches for patterns and interconnections as a way of making meaning.

Students who take full course offerings in science (often earth science in middle school, followed by a biology-chemistry-physics sequence in high school) do the best on science content tests. But most U.S. students do not take the full sequence. Since many U.S. students only take two years of science in high school, a curriculum examining real-world problems as a context for learning science can provide the following student benefits:

- Increased motivation due to personal investment through a science-technology-society, orientation
- Use of higher-order thinking skills
- Development of learning-how-to-learn skills (e.g., problem definition, information gathering, data analysis, making inferences, drawing conclusions)
- Authenticity of the learning experience

A two-year integrated course in science offers students a general background in all science disciplines that may better allow them to compete with students from other nations.

Classroom Implications

The natural world is not segmented into separate disciplines. Learning science through an integrated science curriculum better prepares students to become citizens of an increasingly complex world. It allows them to create conceptual connections that would be less likely to appear while studying the disciplines individually. Integration of science instruction from various disciplines better reflects the overarching concepts and unifying principles of science.

Integration makes science more appealing to a diverse group of students. Integrated science classes tend to be more relevant to them, and to provide them with authentic learning opportunities through real world problems. Possible organizational approaches when designing integrated science curriculum include: overarching, unifying concepts and processes (e.g., systems, patterns); societal issues; research projects; and topics of interest.

Implementation of an integrated science curriculum requires planning, commitment, and support. Integrated instruction and curricula assist students with making conceptual connections when they

- Are designed at the school by people directly involved with science instruction
- Focus on a theme or project
- Develop understanding from concrete to abstract
- Link to content identified by national or state standards

New instructional strategies require targeted professional development (which could include experiencing the new curriculum as a learner, developing the new curriculum, or teaching replacement units), and may necessitate examination of teacher credentialling and certification. With the current misalignment of assessments and standards, changes in assessment must be aligned with changes in curriculum. These changes could affect graduation requirements and pupil credits.

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How can studying technology be included in the science curriculum?

Attempting to teach science without incorporating a study of technology would present an inaccurate picture of science.

Research and Best Practice

Science and technology are interdependent disciplines that represent distinct ways of looking at the world. Attempting to teach science without incorporating a study of technology would present an inaccurate picture of science. Science is one way of answering questions and providing explanations about the natural world. Technology modifies the natural world by producing tools and techniques (ways of doing something) to address human needs, create a desired product, or solve human problems.

The processes of inquiry in science and of design in technology have similarities and differences. Scientists use technological tools to extend their senses for more accurate measurement, clearer observations, and stronger investigations. (Instructional technology, defined elsewhere in this book, includes tools and instruments used in learning science.) Engineers solve problems through technology. These solutions are temporary, and can be supplanted by better solutions. Technology exists in nature, so is subject to scientific study and draws from scientific knowledge. Technological designs have risks and side effects, thus can be analyzed for costs and benefits. Technological designs have constraints, and solutions have consequences. These play out in the social arena.

Science and technology are reciprocal. As science progresses, it can drive the need for more sophisticated technological design, while providing knowledge necessary to create the design. Technology provides instruments and techniques that enhance the capabilities of scientific researchers in observation, inquiry, and data analysis. Scientific discoveries often play a part in technological advancements, and, conversely, technological advances frequently contribute to scientific progress.

Content standards define desired learning in science and technology. Students learn the relationship between science and technology and the ways in which people are involved in both disciplines. Studying the designed world increases students' understanding not only of technological objects and systems, but of how they work. These content standards connect students to the real world.

Classroom Implications

Science teachers need to be aware of various standards related to science and technology. The *National Science Education Standards* and Project 2061 *Benchmarks* contain content Science and Technology standards and Nature of Technology benchmarks for all grade levels. These standards include abilities of technological design and understandings about science and technology. The design standards introduce students to the design process, and improve their abilities to solve design problems. Design problems require applying knowledge, communicating ideas, and implementing procedures.

Students may respond better to the concrete aspects of technological design problems because they are practical and outcome oriented, as opposed to the more abstract, theoretical understandings required in studying science. Using technological tools is sometimes a motivator in scientific investigation for some students.

Misconceptions exist about the interrelationship between science and technology. Some students believe that science represents progress, while technology presents more problems. Other students may define technology as "applied science" without realizing that technology positively influences the progress of science.

Addressing technology content standards requires some thought by the teacher. Involving students in a complete design process may take more time than can be allotted in the unit schedule. Selecting the design task requires decisions about how to show the interrelated roles of science and technology. Over the entire science curriculum, design tasks should cover a range of human needs, materials, and related science aspects. Technology instruction may be analytic or creative but will always involve decision making and valuing. Although the study of technology in science classes should not be extensive, it should be of the highest educational quality. The standards can guide teachers in selecting appropriate activities and conducting stimulating discussions about the designed world.

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How does classroom curriculum connect to the outside world?

Experiences in the community ... make science topics relevant and compelling.

Research and Best Practice

Many fascinating science experiences are outside the classroom doors. Experiences in the community, such as interacting with natural phenomena and doing collaborative research, make science topics relevant and compelling for students. Community resources such as museums, nature centers, zoos, and aquariums offer learning environments not available in the classroom. Scientists and engineers working in the community are themselves resources and role models.

Environmental education integrates life, earth, and physical science topics and can raise authentic personal and social responsibility issues. Today's children need to know and appreciate the natural world if they want to live in and leave a cleaner and healthier planet than the one they inherited. Whether a landfill, a nature trail, or an amusement park, each venue provides numerous opportunities for teachers to relate the curriculum to the interesting and exciting aspects of the outside world.

Varied experiences and interaction with scientific role models can result in increased student motivation and more positive attitudes toward science learning. After positive interactions, students report being able to "see" themselves as scientists and, subsequently, apply more effort and determination to studying science. One of the most valuable contributions of scientists is their modeling of scientific inquiry. In both professional development courses for teachers and classroom interactions, scientists model their abilities to find testable questions, identify resources for investigations, and draw conclusions from data. When reflecting on their own ongoing work, scientists also illustrate that science is a dynamic process, with new information being found every day.

Teachers are challenged with keeping students focused when outside the classroom. Practices that have been found productive include allowing the students to pursue their own questions or experiences without the usual time limits or evaluation; preparing the students for observing, comparing, or organizing data with challenges or preselected questions; and planning for discussion and reflection.

Classroom Implications

Science teachers should explore community resources for connections to the curriculum – from the playground or neighborhood to the laboratories of industries or universities. Phone book yellow pages can uncover resources beyond the obvious museums and nature centers. Physical science phenomena abound in amusement parks and construction sites.

Field trips allow students to encounter authentic scientific inquiry, be active participants in exploring scientific phenomena, ask their own questions, collect and organize data, and discuss their findings with their fellow explorers. Docents, naturalists, and researchers are often skilled in handling student questions in a manner that supports scientific inquiry. Field experiences can connect to classroom learning by providing question-raising experiences at the beginning of a unit of study, opportunities to make observations and collect data to bring back to the classroom, or culminating experiences that reinforce course concepts.

Teachers may extend classroom experiences through virtual field trips online or CD-ROMs. This allows students to not only visit far-away sites, but also to experience simulations of dangerous or rare events. Many students benefit from the opportunity to repeat these virtual experiences.

Students can also participate in actual research through Internet-based global projects. Classroom data collection could help track bird migration and other behavior, compare weather data with others, or contribute to cleaner waterways by sharing local water samples with scientists. Classes can even compete to send their experiment on the space shuttle. Even the youngest students can participate in community decision making by tackling a real problem, designing data collection, and organizing the results for a presentation to community leaders.

A lecture by a visiting scientist can be helpful if students prepare questions in advance, but a hands-on activity led by the visitor is even better. Scientists can make science's processes more understandable, and help students understand how their classroom studies relate to a future career in science or engineering. Positive role models can change the image some students may have of a scientist to a more desirable, dynamic one.

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How can evolution be addressed in the science classroom?

Science is almost always the study of the evolution of systems over time.

Research and Best Practice

In most countries, science teachers routinely include the topic of evolution in their lessons. Evolution is the central organizing principle for biology and is an indispensable concept in all sciences. Science is almost always the study of the evolution of systems over time. Biological evolution, the inference of common descent of living things, explains two of the most fundamental features of the natural world: similarities among living things and the diversity of life. Evolution – the most accurate scientific explanation for the variety of living things – results from the research and experimentation of thousands of scientists for more than a century. Scientists debate how evolution occurred, not whether it occurred.

In the U.S., however, teaching evolution evokes bitter political and religious controversy. In few other countries is the teaching of evolution subject to nonscientific, non-pedagogical pressures. This extra-scientific controversy in the U.S. is mainly a K–12 problem. At many universities, faculty members with science content knowledge design the curriculum, while at K–12 levels, school boards and politicians, who often do not understand the logic and structure of science, are involved. The controversy persists because evolution evokes emotional feelings.

Science and religion are independent and have different ways of addressing issues. The National Academy of Science states that "the root of the apparent conflict between some religions and evolution is a misunderstanding of the critical difference between religious and scientific ways of knowing. Religions and science answer different questions about the world" (p.58). Science explains what the natural world is made of, the natural processes, and how these processes work. Religion addresses issues of ultimate meaning and moral values. Religious knowledge usually remains unchallengeable by observable evidence. Because science and religion have different structural bases, one cannot replace the other, for they serve different functions. None the less, the two are often pitted against each other.

Classroom Implications

The goal of the U.S. science education system is to give all children the best education possible, based on accurate, up-to-date information and broad, content-specific goals. The long-term goal of science education should be to teach all students about science as a body of knowledge and as a way of knowing about the natural world based on evidence from observations and experimentation. Schools have an obligation to teach the best science there is. The First Amendment to the U.S. Constitution prohibits teachers from advocating religious ideas – e.g., forms of creationism – in the public schools.

Both students and society benefit when students are presented the accepted view of science in a standards-based curriculum. A standards-based curriculum is one that teaches children up-to-date, accurate information that is accepted in the scientific community – not a curriculum determined by pressure groups. A good curriculum requires teachers and students to use scientific standards (evidence and inference), rather than dogma and unsupported opinions, in classroom discussions. The *National Science Education Standards* from the National Research Council, the *Benchmarks for Science Literacy* from the American Association for the Advancement of Science, and the National Science Teachers Association, all cite evolution as a central unifying principle, and include it as a content standard.

Emphasizing inquiry and the nature of science in science classes strengthens the public's understanding of science. The teaching of evolution offers educators a superb opportunity to illustrate the nature of science as inquiry and the role of unifying theories. Learning about the historical development of the concept of evolution also offers an opportunity to differentiate science from other human endeavors. In the long run, science literacy will suffer if evolution is omitted, qualified, or de-emphasized in science curricula.

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What ethical and societal considerations are necessary in teaching science?

Science education should help students become aware of their responsibilities as citizens and the role science can play in the community.

Research and Best Practice

Scientific literacy is often defined as the knowledge of significant science facts and principles, the ability to apply that knowledge in everyday situations, and an understanding of the characteristics of science and its interactions with society. Thus, the goal of science education should be to help students develop scientific literacy in order to prepare them to use science for improving their own lives and for coping in an increasingly technological world. Science education should help students become aware of their responsibilities as citizens and the role science can play in the community.

Scientific literacy will help students deal with the explosion of information that is coming from research laboratories around the world, as reported and sometimes distorted in the press. For example, the genetics engineering revolution occurring today will create ethical questions, many of which will be posed to a scientifically-challenged society by journalists who may not only misrepresent the information but also sensationalize the implications of new scientific information. In 1997, for example, the cloning of a lamb from the genetic material from an adult sheep's body cells highlighted the possibilities of biotechnology for the media, government agencies, and the general population.

Ethical questions require thoughtful deliberation and decision making by all elements of society. The potential level of impact of today's biology on people's lives is at odds with the public's level of knowledge about the magnitude and complexity of the problems that are likely to arise as a consequence of new research. There are many potential sources for the information students will need to understand this new and complex situation, the skills they will need in order to analyze all sides of the story, and the ability they must have to weigh risks and benefits of various solutions. These include the media, religion, ethnic and cultural sources, and science education.

Classroom Implications

Students should be able to examine the relationship between science and societal values. New scientific knowledge has the power to change values or to provoke conflicts between value positions that were previously not in opposition. Students will have to make choices based on values informed by scientific information. They will have to resolve conflicts between scientific information and personal ethics. Students' decisions should be based in knowledge as well as values. Knowledge should be used to adopt reasonable attitudes, which, in turn, may lead to responsible actions. Thus, the interrelationships between knowledge and values have an impact for curricular decisions.

Many of the questions students must ponder have a reciprocal relationship. For example, how will cultural and historical values determine the use of genetic testing, and how will genetic testing influence cultural values?

Students need to have skills to resolve all types of issues, even ones that cannot be anticipated at this time. It would be impossible to cover or treat each problem individually: therefore, problem-solving and critical-thinking skills are of paramount importance.

Students need to see ways of connecting the scientific and practical-ethical spheres, between what is and what ought to be. Topics that stimulate student issues and questions should be considered for infusion into the science curriculum, including: patenting biotechnology products, scientific integrity and conflict of interest, the Human Genome Project, genetic screening for diseases and predispositions for diseases, gene therapy, use versus conservation of natural resources, reproductive choice, environmental ethics, protection of endangered species, maintenance of biodiversity, development and abatement of environmental pollutants, and fetal tissues research.

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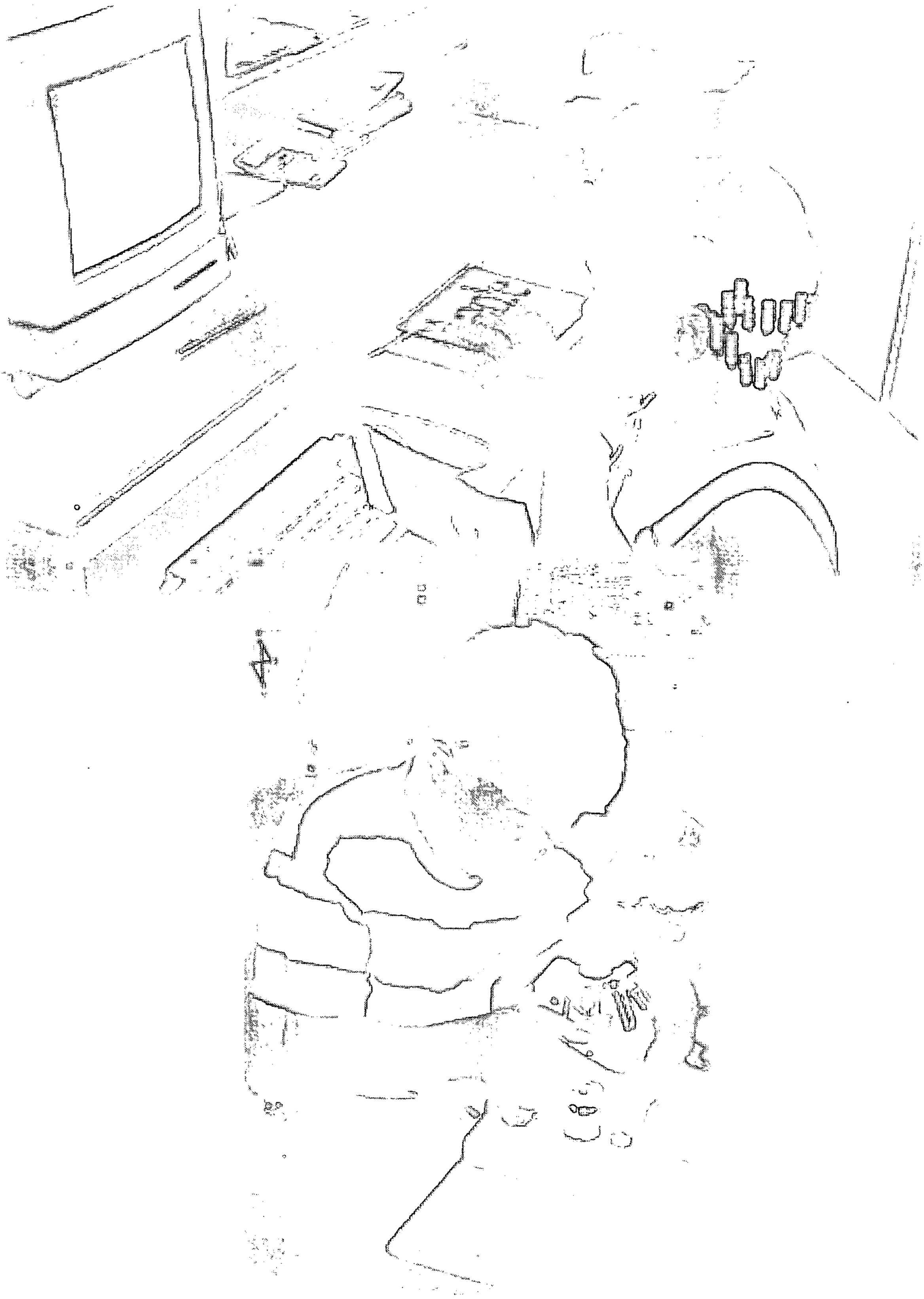

Instructional Technology In Science

Instructional technology refers to certain tools used to promote classroom learning. In science teaching, instructional technology is used to conduct inquiry, thereby making the learning experience more science-like. Specific technologies include measurement instruments such as hand-held data collection devices, calculators, computers, associated software, and the Internet.

Benefits of the use of instructional technology include increased accuracy and speed in data collection and graphing, real-time visualization, interactive modeling of invisible science processes and structures, the ability to collect and analyze large volumes of data, collaboration for data collection and interpretation, and more varied presentations of results. Instructional technology can make science class more meaningful and standards more attainable for all students. The Science Teaching Standards in the *National Science Education Standards* (*NSES*) recommend the use of various instructional technologies in order to facilitate learning.

How can using instructional technology affect science inquiry teaching and learning?

Teaching that reflects the current inquiry standards can be made even more effective by the appropriate use of technology.

Research and Best Practice

The past decade of research on instructional technology has resulted in a clearer vision of how technology can affect science education. Combined with research findings that build a strong case for inquiry-based science, technology is shaping science teaching and learning in profound ways.

Studies show the greatest impact occurs in an environment where students are using the technology to investigate questions or problems of interest to them. In other words, they are directly involved in doing science. The *National Science Education Standards* advocates inquiry as both a means to learn content and an essential ability to do science, much in the same way it is performed by scientists.

Technology provides access to up-to-date digital content, as well as an array of tools for modeling, visualizing, collecting and analyzing data, and enhancing communication. The Science as Inquiry Standards in the *National Science Education Standards* describe students' appropriate developmental use of technology as a tool for conducting inquiry:

- Grades K–4: Children develop skills in the use of computers and calculators for conducting investigations. (p. 122)
- Grades 5–8: Students should be able to access, gather, store, retrieve, and organize data, using hardware and software designed for these purposes. (p. 145)
- Grades 9–12: A variety of technologies, such as hand tools, measuring instruments, and calculators, should be an integral component of scientific investigations. The use of computers for the collection, analysis, and display of data is also a part of this standard. (p. 175)

Technologies with extraordinary capabilities are becoming increasingly available to teachers and students. Despite these powerful teaching and learning tools, the role of teachers as inquiry guides for student learning will become more important, not less. Technology is helping teachers come closer to the national goal of reaching all students with inquiry-based science content and processes that reflect the connected and digital world within which students are growing up.

Classroom Implications

The use of instructional technology has little impact on students learning science if teaching does not move toward more student-centered, inquiry-based practice. Teaching that reflects the current inquiry standards can be made even more effective by the appropriate use of technology. In a technology-rich, inquiry-based classroom

- Technology is viewed as an essential tool for gathering, storing, manipulating, analyzing, and displaying data
- Students of all abilities and diverse backgrounds are engaged and motivated
- Rich multimedia science content that meets all students' distinctive learning needs is available
- Online resources are used to broaden and extend students' own hands-on activities and locally grounded inquiry
- Students are immersed in data – both their own and data collected by scientists or exchanged with other students, classes, or schools
- Technology is used to augment communication by expanding audiences, creating powerful visuals and sounds through display media, and creating networks for exchange of information and collaboration

A variety of technologies can promote the practices listed above. For example, visualization tools and simulation software allow students to "see" and "manipulate" objects and phenomena that would be difficult or dangerous hands-on experiences in the real world. Microcomputer-Based Labs (MBL's) and handheld data collection devices allow students to devote more time to experimental design and interpretation rather than spending excessive time doing data collection. The Internet allows students to experience communication as scientists do through collaboration, access to information databases, and researching scientific findings. These and other technologies help students refine their understanding of science concepts and build new knowledge.

A 1999 issue of ENC *Focus* (available at the ENC Web site) which had as a theme "Integrating Technology in the Classroom" contains articles, materials, and resources on the use of technology in mathematics and science teaching and learning. This document can serve as the basis for planning how to use technology in the science classroom. It can also be a resource for educators experienced in the use of instructional technology, offering new ideas and suggestions of best practices.

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How can technology make science learning more student-centered?

"Computers have become an essential classroom tool for the acquisition, analysis, presentation, and communication of data in ways which allow students to become more active participants in research and learning."

Position statement on the use of computers in education. Adopted 1992. National Science Teachers Association. www.nsta.org

Research and Best Practice

Instructional technology empowers students by improving skills and concepts through multiple representations; enhanced visualization; increased construction of science meaning; and individualized and customized diagnoses, remediation, and evaluation. Technology allows students more autonomy in practicing higher-order thinking skills. Increasing access to primary resources, large data sets, and museum-quality collections opens opportunities for students to select learning contexts and design investigations.

By allowing experimentation, manipulation, and testing of ideas, instructional technology provides concrete feedback, often instantaneous and personalized, about the accuracy of learners' ideas. This permits students to proceed with learning, without needing teacher approval. Increasingly, software allows students to suggest solutions and simulate their effects, improving the quality of solutions offered. By facilitating active learning with technology, teachers can pose problems, students can respond individually, and classroom data sets can be generated. Students are able to collaborate with peers or experts as they inquire about problems, gather data, and give feedback on solutions and strategies.

Technology enriches the range and quality of investigations by showing multiple perspectives on abstract scientific ideas and exciting real-world problems. Instructional technologies create an active environment in which students not only inquire, but also define problems of interest to them. Students using these technologies have produced impressive intellectual achievements and report enthusiasm and motivation for learning.

Many instructional technologies are tools for problem-solving. Calculators, spreadsheets, graphing programs, probeware, and programs modeling complex phenomena provide cognitive scaffolds to promote complex thinking, design, and learning. Such activities are often motivating because they are learner-focused and authentic, they encourage critical thinking, and they create lasting knowledge.

Instructional technology broadens the learning community. When students collaborate, they share the process of constructing ideas. This encourages learners to reflect on their ideas in ways generally not seen in classroom instruction. Current interests can be productively pursued; timeframes do not hinder; intellectual barriers can be broken down; and creativity, individuality, and desire to learn can be maximized.

Classroom Implications

When student science experiences are integrated with technology, the role of the teacher changes from delivering content to a student-centered approach. The teacher becomes a facilitator, moving throughout the classroom, assisting individual children or the group as a whole. The teacher's role is to help students internalize concepts presented in scientific or mathematical symbols, or in graphs and other external representations of these concepts discovered through technology.

Teachers need to allow time for students to develop concepts and an understanding of science. As an example, students may be concerned about the quality of water sources in their community. They can collect data on water pH levels down the length of a nearby stream and graph their findings. Activities like this are learner-focused and authentic, encouraging critical thinking and creating knowledge that is lasting and useful. Using technology allows students to employ a variety of strategies such as inquiry, problem-solving, creative thinking, visual imagery, critical thinking, and reasoning; hands-on abilities such as measuring, drawing, sketching, working with computers, and using tools; and quality control mechanisms such as continual and appropriate assessment and evaluative techniques.

It is not the equipment in the classroom, but how the equipment is used that makes the difference in student understanding. For example, tools such as graphing software allow students to construct scientific knowledge rather than memorize facts dispensed by the instructor. The key to success lies in finding the appropriate points for integrating technology into science, so that it supports the understanding and reflection students must do.

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How can using instructional technologies make science learning more science-like?

Science learning becomes authentic when students investigate real world, meaningful scientific problems.

Research and Best Practice

For decades, a goal of science education has been to make science learning resemble science practice. Now, with the increasing availability of computer and other technologies for the classroom, as well as the expanding role of these technologies in science practice itself, there are new opportunities for experiencing real-world science in K–12 learning environments. Science learning becomes authentic when students investigate real world, meaningful scientific problems. In the same ways that technology has increased the efficiency and scope of practicing scientists, it can also improve student learning in experimental settings, making learning more effective while providing a more accurate view of the conduct of science.

National standards emphasize the importance of student inquiry in teaching. *Benchmarks for Science Literacy* asks that students be able to "frame the question, design the approach, estimate the time and costs involved, calibrate the instruments, conduct trial runs, write a report, and finally, respond to criticism" (p. 9). Similarly, the *National Science Education Standards* emphasizes inquiry: "For students to develop the abilities that characterize science as inquiry, they must actively participate in scientific investigations" (p. 173). The *NSES* definition of inquiry, "asking questions, planning and conducting investigations, using appropriate tools and techniques to gather data, thinking critically and logically about relationships between evidence and explanations, constructing and analyzing alternative explanations, and communicating scientific arguments" (p. 105), is similar to the *Benchmarks'*.

National standards identify two different kinds of student inquiry: "inquiry-based learning" and "extended inquiry," which models the way science in the real world is carried out. The former is a teaching technique that should be used pervasively at all grades. Students should have their first experience with most major concepts in science in an experimental learning context where they can ask their own questions and construct their own understandings. Extended inquiry expands this idea, recommending that students have opportunities to undertake real research projects that extend over weeks. This gives students unique opportunities to experience for themselves the process of working with science as scientists do.

Classroom Implications

Scientists use various forms of technology to collect data, build models, visualize data, and communicate their findings. As science classrooms became more science-like, teachers will provide students with activities that differ from those now typically in the curriculum. Rather than reading a text and answering written questions, students will be out in the field using probeware to collect data. They will use computer software to model or graph the data, and then word process a report of their conclusions. In other words, they will be using technology in the same ways scientists use it.

The Internet and other communication technologies provide opportunities for students to collaborate as most scientists do – not by doing experiments together, but by sharing data and hypotheses, and building on results from other groups. E-mail and videoconferencing link student scientists anywhere in the world so that science becomes a global endeavor.

Technology is essential to implementing extended inquiry. Unlike traditional textbook-based curricula, there is no way to know where an extended scientific investigation might lead. Just as in real science, student projects can lead in directions and require measurement tools and analysis strategies that are unanticipated. The technology tools explicitly mentioned in the *National Science Education Standards* as supporting inquiry include MBLs (probeware), spreadsheets, data analysis and graphing software, modeling software, electronics, and instrumentation.

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How can students learn to assess the credibility of Internet information?

Research and Best Practice

Today's students are the most informed generation in history. The Internet gives them immediate access to information, sometimes even as events are unfolding. With all this information at their fingertips, how can students determine its credibility?

"Skepticism is not just a matter of willingness to challenge authority, though that is an aspect of it. It is a determination to suspend judgement in the absence of credible evidence and logical arguments."

American Association for the Advancement of Science, Project 2061, 1993, p. 287.

The *National Science Education Standards* call for teachers to "make the available science tools, materials, media, and technological resources accessible to students" (p. 43). *Benchmarks for Science Literacy* describes "skepticism" as an important scientific habit of mind which should be developed in all students. Similarly, the *National Education and Technology Standards* calls for students to evaluate information gathered in light of its appropriateness.

The AAAS's *Science for All Americans* describes ways everyone can learn to detect dubious assertions, strategies which are particularly applicable to assessing scientific claims and information students may encounter on the Internet. Students can detect less credible information by looking for the following signs:

- Premises of arguments are not explicit.
- Evidence does not lead logically to conclusions.
- Fact and opinion are not clearly distinguished.
- Celebrity is quoted as authority.
- Specific references are vague or missing.
- Graphs are misleading.
- Measures taken to guard against distortion in self-reports are not described.
- Percentages are given without stating total sample size.

Scientifically literate students will respond appropriately to the barrage of information that technology provides. Separating sense from nonsense is a critical response skill that must be developed in all students.

Classroom Implications

Most students in this Information Age believe that everything they need is on the Web, accurate and free of charge. Teachers must help students learn techniques to assess this ever-expanding source of data, so that they can be informed consumers of information on the Web. A comprehensive plan defining appropriate uses of technology should include teacher goals and student goals aligned with the district curriculum. Both teachers and students should evaluate potential Web sites using criteria that fit the objective of the project. These criteria should include the accuracy, authorship, objectivity, timeliness, and usability of the site. Unless the goal of a lesson is to evaluate the credibility of resources, many leading educators suggest providing a list of carefully screened Web sites for students to focus on initially.

The Internet, with its vast volume of digital information, has pros and cons as a curriculum resource. Both teachers and students must learn to be critical consumers of digital content. Teaching students how to assess the credibility of sources not only ensures that students will develop appropriate conceptual understanding, but that they will also develop a lifelong habit of mind that is a hallmark of scientific thinking. Although not all students will become scientists as adults, this critical attitude can be applied in everyday life, whether in relation to health care choices, global implications of technology use, or the commercial claims they encounter.

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How can technology professional development impact science learning?

"Both students and teachers need to master skills that weren't necessary in the last century but are vital in the new one."
Dede, 2000, p. 171.

Research and Best Practice

One cannot deny the explosive effect technology has had on science. Technological advancements are also affecting the way educators teach and students learn. However, the pace and success of learning is strongly determined by the quality of professional development. Today's science teacher must have the ability to employ technology to improve student learning as well as to further personal professional development.

Teacher quality is the factor that most influences student learning. Studies show that effective use of technology does improve academic achievement, attitudes, and self-concepts. However, gains in student achievement associated with the use of technology are dependent on teachers who are proficient in its use themselves. Professional development is critical to ensuring teacher proficiency. Professional development for science teachers is multifaceted and targets three areas:

- Learning how to use specific software and devices
- Learning how to successfully infuse technology into science teaching
- Using technology for teacher learning, particularly in the science content area

Professional development for technology use in science teaching should contain important components research has found to be critical for successfully changing practice. These professional development features include a connection to student learning, hands-on use, a variety of learning experiences, content and curriculum specific applications, modeling of best practice, collegial learning, and sufficient time for practice and reflection.

Using various forms of technology for enhancing professional learning of science teachers has advanced in recent years. Teleconferencing, interactive television, Internet courses, videotapes, and CD-ROMs provide diverse opportunities for science teachers to expand their content knowledge and improve teaching practice.

Classroom Implications

For teachers to implement classroom technology that increases student engagement and improves achievement, they must seek professional development opportunities that focus on teaching and learning, rather than on the technology itself. Characteristics of quality professional development in the use of instructional technology to impact student learning include

- Opportunities to use technology for deepening students' understanding of science concepts
- Opportunities to become fluent in using technology to develop higher-order thinking and problem-solving skills
- Direct links between the technology and the science curriculum
- Linking technology use to a wide repertoire of teaching strategies
- Time for practice both outside of the classroom and with students

When technology is used appropriately to provide professional development, instead of simply being the topic for professional development, key learning features for teachers are evident:

- Technology presents opportunities for diverse learning experiences. Videos, CD-ROMs, Internet courses, and electronic networks provide alternative settings, resources, experts, and times for teacher learning.
- Technology supports both individual and collaborative learning.
- Technology provides equitable access for all teachers. Teachers in resource-poor schools and isolated geographic areas have access to information and people that were previously unavailable to them.

Technology is touted as a critical ingredient for education in the future, but it is not a silver bullet. Professional developers must think carefully about its implications for teacher learning, when and where it is most appropriately used, and how it can effectively extend the ability to create effective learning opportunities.

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Learning Science

What does it mean to learn science? This question is addressed by the *National Science Education Standards* (*NSES*) and *Benchmarks for Science Literacy*. Science is a physically and mentally active process. Children are natural learners. They explore materials in the natural world, make constant observations of the world around them, and make and test hypotheses about natural phenomena. For children, science is learned by doing. Their school experience of science learning should include hands-on and minds-on inquiry through grade 12, and not strictly lectures, videotapes, books, and worksheets.

During the 20th century, educators' understanding of the learning process has progressed from behavioral observations through cognitive psychology into improved knowledge about neurophysiology. The 1990s were dubbed "the decade of the brain" because of the tremendous increase in our understanding of how the brain works. Twenty-first century educators will apply the newest understandings from neuroscience to improve their classroom practice.

What is the value of learning science in today's world?

"A sound grounding in scientific inquiry strengthens many of the skills that people use every day, like solving problems creatively, thinking critically, working cooperatively in teams, using technology effectively, and valuing life-long learning."
National Research Council, 1996, p. ix.

Research and Best Practice

The value of learning science in today's world must be addressed in the context of scientific literacy for all students. Even though scientists and science educators may differ somewhat in defining scientific literacy, most would agree that scientific literacy encompasses scientific knowledge (facts and principles), the ability to apply that knowledge in everyday situations including personal decision making, and an understanding of the nature of science and societal implications. Scientific literacy also includes knowledge about technology, especially the design aspect. Students learn that science knowledge is based in observations and experimentation. The scientific inquiry process is unique to science.

The *National Science Education Standards*, *Science for All Americans*, *Benchmarks*, and other documents define what all students need to know and be able to do in today's world and the future world. The *NSES* provides the specifications and framework for the structure of scientific literacy. The goal of science education is to help all students use science to improve their own lives, become aware of their responsibilities as citizens in a democratic society, and understand how science can impact future careers. Science education should create windows to the world and mirrors to help students reflect upon their personal experiences.

The Glenn Commission Report, *Before It's Too Late*, cites four reasons why students should become competent in mathematics, science, and technology. First, rapid changes in the integrated global economy and the American workplace demand widespread science-related knowledge and abilities. The future workforce needs different skills than earlier employees. Sixty percent of new jobs in the early twenty-first century will require skills possessed by only twenty percent of the workforce. A second reason for science competency is for everyday decision making. Future citizens need to be scientifically informed to understand and solve problems such as cloning, genetic manipulation, use of DNA in legal decisions, nutritional supplements, new drugs, global warming, and destruction of the ozone layer. Third, our national security is linked to science, mathematics, and technology. Finally, scientific knowledge shapes and defines our history and culture. Science helps us understand the predictable nature of our world and is a tool for creating progress.

Classroom Implications

Scientific literacy is the goal for all students, not just for those preparing for college or those who will become scientists. Science learning expectations must be high for all students. Scientific literacy includes using science-related knowledge on a personal and societal level, addressing science issues by asking questions, using evidence to propose explanations or answers for these questions, and becoming informed citizens in a democratic society. To promote the goal of scientific literacy for all students, the entire K–12 educational system must be aligned and focused on providing

- Important content or the big ideas of science
- Active learning where students begin with questions about the natural world and use evidence to propose explanations or answers for those questions
- Connections across scientific disciplines, technology, mathematics, social sciences, humanities and civic responsibilities
- Preparation for future careers
- Tools and strategies to assist with personal decisions on science-based issues

Alignment of the K–12 educational system includes the six areas addressed in the *National Science Education Standards*: Teaching, Professional Development, Assessment, Content, Program, and System. To offer high quality, K–12 science education experiences for all students, there must be a consistent and coherent program taught by content-qualified teachers. Ongoing professional development opportunities provide teachers with learning experiences needed to teach science effectively. Administrators need to offer positive support, such as providing access to science resources; ensuring that a qualified, highly competent science teacher is in every classroom; and promoting ongoing opportunities for professional development.

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What do we know about how students learn science?

The science classroom should provide rich opportunities to investigate contextual problems.

Research and Best Practice

In the past decade, educators have greatly improved their knowledge of how students learn science. They place increased emphasis on learning for understanding rather than memorization of isolated facts. Students come into science classrooms with preconceptions about how the world works which often do not coincide with scientific explanations. Students' initial ideas about concepts may also be unconnected or only loosely tied together. Teachers need to determine students' initial understanding about science concepts in order to lead them to a more complete understanding of concepts, provide strategies to retrieve knowledge and make connections, and address misconceptions. As students gain a deeper understanding of concepts through in depth experiences, factual knowledge becomes useful. To facilitate learning, students also need to develop metacognitive strategies that include predicting outcomes, thinking about failures to assist with comprehension, activating background knowledge, and planning ahead.

Brain research gives educators additional information about learning. For example, the brain processes short chunks of information rather than single words or long streams. Therefore, each learning experience should be organized to present small coherent units of information. Strategies such as graphic organizers, peer teaching, role playing, and summarizing information help students build understanding.

Different types of learning opportunities are necessary to develop more in depth understanding of concepts and thinking skills. These opportunities include learning by doing (experiential), symbolic learning which is the more traditional text or paper and pencil approach, and use of pictorial or graphic representations (e.g., maps, films, videos, CD-ROMs, drawings). A learning cycle approach to lesson planning includes an exploration phase, concept introduction, and concept application. Hands-on experiences help students make meaning about scientific phenomena and help students move from more concrete to abstract levels of thinking. Ongoing learning assessment with timely focused feedback helps students attain deeper understanding.

Classroom Implications

Effective science classrooms provide rich opportunities for students to investigate contextual problems with the goal of understanding concepts and developing inquiry-based thinking skills rather than learning isolated, disconnected facts. Subject matter should be taught in depth using a learning cycle approach that includes exploration, concept introduction and concept application. Teachers first draw out and address students' preexisting scientific understandings. Then, students engage in tasks that reveal their thinking. Students need to experience multiple examples in which the same concept is at work; this provides a firm foundation of factual knowledge for concept formation. Hands-on activities assist students with making their own meaning about scientific phenomena. Formative assessments provide feedback to students and teachers about student learning.

Metacognitive strategies that can assist students with deeper understanding of concepts and terminology include: graphic organizers, peer teaching, questioning strategies, summarizing, note taking, role playing, debates, timelines, mnemonic devices, and paraphrasing. Both individuals and groups are engaged in inquiry activities. Teacher questioning elicits students' thought processes and gives students opportunities to develop greater clarity and precision. Changing the form of a question from one requiring a single right answer to one that allows students various ways to achieve end results increases student understanding, creativity, and motivation.

Students need school time for regular, sustained engagement in the study of science, including meaningful practice of inquiry skills built on understanding. The optimal learning environment for science also helps students make connections to the outside world. Parents and other community resources become important partners in giving students more responsibility for their learning.

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Can all students learn science?

"[The Standards] emphatically reject any situation in science education where some people are discouraged from pursuing science and excluded from opportunities to learn science."

National Research Council, 1996, p. 20.

Research and Best Practice

Standards-based education reforms derive from principles of excellence and equity. This broadens the goal of science education to include all students, not just some. The standards' learning goal is science literacy—what all adults need to know to function as citizens. Some teachers and parents, even some students, doubt that all students can learn science. However, providing a substandard science education for some students is not acceptable. Learning research provides many proven techniques for helping all students achieve success. Researchers from many fields compiled 14 learning principles that can inform school redesign and reform. Science instruction can be made accessible to many more students. Learning styles, gender, culture, learning disabilities, and prior experiences need to be addressed to help all students succeed.

Students must have the opportunity to learn, which means availability of classes and adequate support for success. Most middle and high school students do not now have access to a standards-based curriculum. Surveys in 1998 across all states show that 54 percent of high school students take three years of science (typically earth science, biology, chemistry) and only 24 percent nationwide take four years (measured by enrollment in physics). In 1997-98, 31 percent of grades 7 and 8 students took a general science course, 15 percent took life science, and 12 percent took earth science. In elementary school, a negative teacher attitude can result in little time allotted for science and poor instruction. In self-contained classrooms, teachers report forgoing science instruction in favor of reading and mathematics, areas subject to high-stakes testing. Success in science, especially in high school and beyond, is strongly linked to access to and success in mathematics. Mathematics courses are often prerequisites for advanced science courses. Developmentally, the abstract concepts, problem-solving, and reasoning learned in advanced mathematics enables and enriches the study of science.

Negative attitudes are a barrier to success. Some students perceive themselves as unable to succeed due to innate lack of ability. Reluctant students can be taught about how to learn and, with some success, change their self-perception and become more motivated. Teachers' negative attitudes may deny students access to the curriculum, actively or passively. Teachers may also have a negative attitude about students' developmental ability to learn, causing lower expectations. However, student development can be brought to the appropriate level through high expectations and learning experiences that meet students' needs.

Classroom Implications

Meeting the challenge of maintaining high expectations of and providing effective instruction for diverse groups of students demands a mastery of pedagogy as well as content, and a portfolio of varied teaching strategies. Teachers need professional development that models proven strategies, access to and time to reflect on research, and time with colleagues to discuss progress toward the shared goal of increased student achievement.

Assessment information can provide concrete guidance on what students know and are able to do. This information may be gathered effectively by activities that cause students to reveal what they already know about a topic, as well as their misconceptions. Not all assessments need to be written tests. Teachers can observe students during a learning activity for certain skills, vocabulary, or conclusions. Students' data sheets, drawings, or journals can be studied for assessment information. Conversations and questioning by the teacher directly assess what a student understands. Assessments at the beginning of a unit or during the course of a learning cycle are most valuable for tailoring instruction to ensure that all students are learning.

Students need time to really understand science concepts – to explore, experiment, ponder, and apply knowledge in new contexts. To the extent possible, the number of topics to be covered should be small, perhaps combined into integrated units of study.

Peers can be resources for learning when a classroom environment is structured for that purpose. Cooperative learning methods can help support language learners, students with physical challenges or learning disabilities, and students in large classes who might otherwise get less teacher attention. Students with various learning styles respond well to choices in how to study a topic and how to show what they are learning. Likewise, multi-age grouping can provide more opportunities for support.

Parents are important allies in ensuring that all students learn successfully. Parents can provide teachers with valuable information about a student's past experiences and how he or she learns best. As educational partners, parents can provide home activities to reinforce classroom learning or provide alternative structure or experiences. Parents must be advocates for students who are being denied the opportunity to learn science.

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How can teachers help students reflect on and communicate their own learning?

Learning increases after direct instruction in metacognitive strategies.

Research and Best Practice

Metacognition, sometimes referred to as thinking about thinking, is an excellent way to assist students both to reflect on and to communicate their learning. As ways to manage thinking, metacognitive strategies include

- Connecting newly learned information with that already known
- Carefully choosing appropriate thinking strategies for a specific use
- Planning, monitoring, and judging the effectiveness of thinking processes

Learning increases after direct instruction in metacognitive strategies.

Creating and maintaining portfolios of personal work is one strategy that encourages reflection. The process of selecting and organizing the contents of a portfolio builds self-awareness. The use of classroom portfolios gives students more control over their own learning. It also supports teacher professional development, shifting the emphasis from instruction to facilitation of learning.

Writing is another way for students to discover, organize, summarize, and communicate knowledge. Writing makes thinking processes concrete and increases retention of concepts. The act of writing gives a student access to his or her own thinking processes, enabling the construction of new understanding that is meaningful and applicable. Writing assignments in science have been shown to generate reasoning about data.

The process of editing writing produced in science class clarifies both purpose and understanding. The editorial process serves as feedback, inspiring reflection.

The use of metacognitive strategies, portfolios, and structured classroom writing assignments supports student's personal construction of science understanding.

Classroom Implications

Metacognitive activities in science classes can ask students to

- Identify what is known and not known (e.g., KWL – what I know/want to know/learned)
- Talk about thinking (first through teacher modeling, then in group discussion, culminating in paired problem-solving)
- Maintain a thinking journal or learning log (e.g., a process diary)
- Take increased responsibility for planning activities
- Practice targeted self-regulation skills following direct instruction (e.g., estimating time requirements, organizing materials, scheduling)
- Debrief thinking processes during class closure (e.g., review thinking processes, identify and classify strategies used, evaluate successes, seek alternatives)
- Participate in guided self-evaluation

Metacognitive strategies, which are most useful when learned responses are inadequate or inappropriate, are developed through inquiry and research.

Writing tasks must be authentic: that is, the text must address a real audience, sometimes oneself. A journal can be used to reflect on knowledge, feelings, and beliefs. It can open a dialogue between learner and teacher that leads to more individualized instruction and support. Throughout the year, topics for journal writing should start with affective, open-ended prompts ("When did you feel most successful at science? Why?"), proceed to a review of familiar scientific ideas ("Explain the water cycle to a third grader."), and move toward discussion of more advanced science concepts, to extend and reinforce new understanding.

Other useful types of writing assignments include analytic essays, which develop links between concepts, and concept maps or hierarchical outlines, which can be used to facilitate meaningful cooperative learning, identify misconceptions, evaluate understanding, and demonstrate construction of scientific knowledge.

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What does brain research tell us about learning science?

Brain research sheds light on the mechanics of learning and on the best conditions for encouraging learning.

Research and Best Practice

Brain research sheds light on the mechanics of learning and on the best conditions for encouraging learning. Physically, human memory consists of connections or synapses among the brain's cells, which are called neurons. The basis for student success in learning science can be derived from understandings about the biochemical processes of memory creation and storage, learning, and complex synaptic connections.

At the biochemical level, learning is the process of accumulating recognizable and retraceable neuron pathways in the brain, as it continuously performs multiple tasks. Every "bit" of learning, whether conscious or unconscious, is recorded immediately by changes in the neuron's structure as additional branching dendrites grow from the nerve cell. Memory storage exists in different regions of the brain depending on the material being remembered. Memory retrieval and the application of stored information to new situations can be more easily accomplished when neural pathways are frequently used.

The human brain is naturally curious, searching for patterns in sensory input and memory. It analyzes complex information into component parts, and synthesizes simple facts into concepts. The brain initially pays primary attention to the emotional content of information, but is capable of being focused through metacognition. Because it is changed by every act of learning, whether intentional or peripheral, each brain is unique. To make appropriate use of brain research on learning, science teachers should link new instruction to students' prior knowledge by employing teaching strategies that draw on varied learning styles.

Classroom Implications

Sensory perceptions are initially received into short-term memory. Learning involves transferring the information to long-term memory and organizing it. New information becomes part of long-term memory in various ways, all of which involve establishing neuron connections. Students may try to store material in memory by repeating it verbatim. This time-consuming method will eventually result in memorization of isolated facts or terms. It is not, however, a good way to create overarching concepts and other important memory structures. Building on the biochemistry of learning, science curricula should repeat concepts, but avoid duplication of contexts. Previously taught material should be used in a new manner or context. Emotionally charged information is memorized faster, a reason to include personal/social material in the science curriculum.

Without appropriate attention, new material will fade from short-term memory unless it is connected to related material already in long-term memory. One strategy for creating comprehension is through the use of analogies. Scientists often develop scientific explanations for their observations by creating analogies with information they already possess. A recommended method of teaching science involves students in processes identical to those used by scientists, including strategies such as using analogies. However, if students do not have the background knowledge scientists do, this "prior" information must be provided through reading, simulations, or activities.

Sometimes students have misconceptions about science topics, which should be corrected through the process of equilibration. This means that long-held concepts should be evaluated in light of new information, a complex and time-consuming process. Some misconceptions appear to be more tenacious than others. Thus effective teaching requires not only sound knowledge of correct science information, but also knowledge of common misconceptions and how to deal with them. Without the latter, students' attempts to combine new instruction with prior misconceptions may lead to unanticipated learning outcomes.

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What can parents do to support student learning in science?

"We encourage... parents and community members to use the Standards to contribute to their children's science education and generate support for high quality school science programs."
National Research Council, 1996, p. 245.

Research and Best Practice

Parent-family involvement increases all students' achievement and success. Parent-family involvement may run the gamut from seeing that homework is completed and that family members know what is going on in the school life of the child, to involvement in local school councils that set policy and regularly review the effectiveness of school operation. Parents can contact businesses interested in supporting science education; be science mentors; locate resources, science materials, and supplies; and coordinate district-wide science events.

A successful parent-family involvement program will result in

- Greater student achievement
- Increased parent-family participation in school activities
- Positive changes in the "climate" of the school, including friendliness and accessibility
- Improvement in student attendance
- Decreases in dropout rates
- Decreases in alcohol use, violence, and antisocial behavior
- Increases in equal partnership efforts among school personnel, parents, and families

The National PTA recognizes parents as the primary influence in a student's life and a necessary partner in their education. Parent-family involvement is an accurate predictor of student achievement and success. This is extremely important in science education. In an increasingly technological world, a growing number of jobs require science and mathematics knowledge and the use of related thinking skills. Informed and active citizens need a solid foundation on which to be able to question, assess, and decide about the many environmental, technological, and safety issues that arise. Parents who nurture their children's natural curiosity and foster interest in the natural world help prepare their children to be active citizens in the twenty-first century.

Parents do not have to be scientists to help their children in science. Being "scientific" means being curious, observing, asking how things happen, and learning how to find answers. Parents who are willing to observe closely, have a positive attitude about science, and take the time to answer questions or seek answers from other resources, will be partners with their children in learning science.

Classroom Implications

Parents and community members are resources for all levels of the education system. Teachers and administrators need to communicate science program goals and the types of support needed by teachers and the school. Parents can fill many school or district level roles depending upon their interests and time to participate. These roles may include

- Assisting students with community-based science problems
- Serving as mentors to students other than their own children
- Supporting outside activities such as visits to museums or nature centers
- Monitoring learning logs
- Serving as a contact with businesses that might want to support science education
- Locating and/or managing resources, science materials and supplies
- Assisting with a school- or district-wide science event
- Doing science activities at home
- Supporting homework activities
- Serving on school or district committees on topics such as policy, curriculum, or research on learning science

For parents and community members to improve the quality of science education, they must: discover what students are doing in science class; conduct informal science activities in their neighborhood or at home; learn more about science education, including standards; support teachers who use an inquiry approach; and share and discuss science education ideas with school administrators, teachers, and other parents.

Science educators should be proactive in involving parents and giving them tools to become more effective "science coaches" for their children. Communicating the goals of science learning activities and changes to science programs is key to building partnerships with parents. Engaging families in science education may require special school events. Family Science Nights have successfully introduced parents to inquiry-based, hands-on science activities that illustrate best practices in science pedagogy. Students design and plan the activities they want their parents to explore. In schools where kit-based science has been implemented, parents can have an opportunity to explore several activities from the kit. Most parents become strong advocates of inquiry science after this engaging experience, and their enthusiasm spreads to their children.

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What are the characteristics of effective homework in science?

A homework assignment should be a major event in student learning.

Research and Best Practice

Every day children hurry home from school and arrive to face the obligatory question from parents, "What did you learn in school today?" They return to school the following day, and their teacher asks, "Do you have your homework assignment?" Perhaps a better question would be "What did you learn at home?" The home should be a place to extend science learning.

Student learning in science should always focus on understanding the set of skills and knowledge needed to investigate the world. Science knowledge is growing too quickly to to learn it as a body of knowledge. We must rely on developing students' science skills to do investigations, which will help them understand the world. These science skills are described as "inquiry" in the *National Science Education Standards* and "habits of mind" in *Benchmarks for Science Literacy*. Science educators and scientists agree that knowing science is more than being able to recall facts. Research indicates that individuals with expertise in science understand science concepts and how to learn from their own investigations and inquiry.

Homework assignments provide the opportunity for students to do long-term projects that require multiple levels of understanding. Students take ownership when they spend months observing an ecosystem, finding the names of organisms in an environment, suggesting ways to maintain diversity in that environment, interviewing wildlife managers and perhaps even taking action to protect the environment. Observing the night sky on one night may be interesting, but when students keep a night sky journal for six months – drawing diagrams, tracing movements, and identifying objects in the sky – their learning will go beyond the curriculum.

Homework time is an opportunity for students to reflect on learning and synthesize their science understandings. Well-designed homework can bring parents and other adults into a student's community of science learners. Assignments should include students discussing their learning with others. This can be done through student learning teams, parent involvement, or the teacher using e-mail to have discussion groups. Science is in every aspect of life. Teachers should take advantage of the opportunity to provide students with authentic learning opportunities at home.

Classroom Implications

The value placed on various aspects of science learning can be seen in the allocation of instructional time in class and by the nature of homework assigned. Teachers who value investigation skills will provide time in class to develop students' ability to do investigations, and then will assign homework that uses these skills in new settings. What goes on in class should match the homework assigned. Science homework should not be school work done at home. The home provides a unique opportunity for students to gain science understanding by doing science investigations.

Teaching for understanding requires assignments designed for understanding. Assignments should have clear criteria and written rubrics that describe expectations and establish student goals.

It is important for students to do their best and for teachers to examine student work. Less is often more when it comes to homework. A product that has been refined by the student results in more effective learning than a large volume of work completed with little thought. The quality of student work is often determined by the standards a teacher sets on the assignment, time spent reviewing the expectations, and suggestions for improvements. A homework assignment should be a major event in student learning. Selling students on the importance of an assignment as a learning event is important: their ownership will determine the depth and breadth of their learning.

Getting students involved in science news events helps students understand the nature of science. Students should be aware, curious, and interested in newsworthy events such as a solar eclipse, shuttle launch, or the discovery of a new gene therapy. Connecting newsworthy science events to the science learning in school helps students take an important step toward science literacy.

The public is fascinated with science and nature. PBS science programs such as "Nature," "Nova," and "National Geographic Explorer" should be part of a student's life. Teachers should encourage students to watch specific educational programs that connect with their science learning. As homework, students can watch and discuss specific educational television programs with their parents and fellow students. School time is far too precious to spend watching a video.

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What is the impact of teacher learning on student learning?

Teachers who continue learning throughout their careers are more likely to become conscious, competent, professional teachers.

Research and Best Practice

One of the strongest predictors of students' success is the quality of their teacher. Teachers who are highly qualified with both science content knowledge and pedogological skills are more effective teachers. Teachers who continue their education while teaching tend to develop a deeper understanding of content applications, content knowledge, effective instructional strategies, theoretical bases for instructional decisions, and confidence in decision making. In general, teachers who continue learning throughout their careers are more likely to become conscious, competent, professional teachers.

The value for teachers to have continual professional growth has been identified in award programs that recognize excellence in science teaching. The Presidential Awards for Excellence in Mathematics and Science Teaching (PAEMST), the Tandy Technology Award, and the Milken National Education Award all place value by using continual professional growth as a criterion for selecting awardees. These programs ascribe a positive relationship between their awardees' classroom teaching excellence and continual professional growth.

The National Science Foundation supports professional development programs that are sustained and impact the classroom learning of students. Programs such as the Department of Energy's Teacher Research Associate (TRAC) program provided teachers with summer research experiences for the express purpose of improving the teachers' understanding of the nature of science. Evaluations of Department of Energy Teacher Research programs found teachers engaged in intensive long-term professional development activities were more likely to find success in their teaching assignment.

The *National Science Education Standards* establishes the rationale for professional development in the Standards for Professional Development for Teachers of Science. Becoming an effective teacher of science is an ongoing process and should be an integral part of a teacher's entire career. Induction into science teaching is an important aspect of this process, but must continue throughout a teacher's career, including continual renewal of both the content and pedagogy skills. Equally important is the engagement of teachers in inquiry of their own teaching practices, their students' responses to these practices, and the relationship between these two elements for all children.

Classroom Implications

A community of learners includes a teacher who is a learner with students. Science education standards that establish goals for students to attain lifelong learning skills, should and do expect as much of teachers.

Teacher learning specific to the science subject matter provides teachers with both the understanding to anticipate and overcome student science misconceptions and the confidence to teach in an inquiry mode. A broad understanding of science provides teachers with one of the key components for the integration of the various fields of science as well as integration across the curriculum. In the process of pursuing advanced degrees, teachers develop the skills and value for development of student writing skills as part of science instruction.

Teachers should make decisions based upon data; the best data for teachers to use is the information that is gathered in the classroom. Teachers who are learners engage in action research to hone their instructional decision making skills. Data collected in the classroom provide evidence that can be used in making instructional adjustments.

Science teachers should stay current in science as well as science education. The classroom is a changing place; the content of science requires ongoing engagement to stay abreast of current research. Biology teachers who have taught for 25 years need only look at the changes in knowledge of genetics since their undergraduate studies to realize the scale of science knowledge growth. Reviewing the growth of knowledge in any area of science makes it clear that continued learning is needed to remain current in science. One way professional teachers maintain a current knowledge of their content area is through memberships in professional organizations. These organizations provide journals that synthesize current topics in science and science education. Popular science magazines such as *Scientific American*, *Discover*, and *Science* provide teachers with current science findings to share with students and increase the interest in the classroom. Often the nature of science is best seen in developing areas of science.

Perhaps the most significant implication of teachers being engaged in learning is the enthusiasm for learning brought to the classroom. Students know when a teacher is excited and engaged in learning. This adds to students' interest and excitement for learning.

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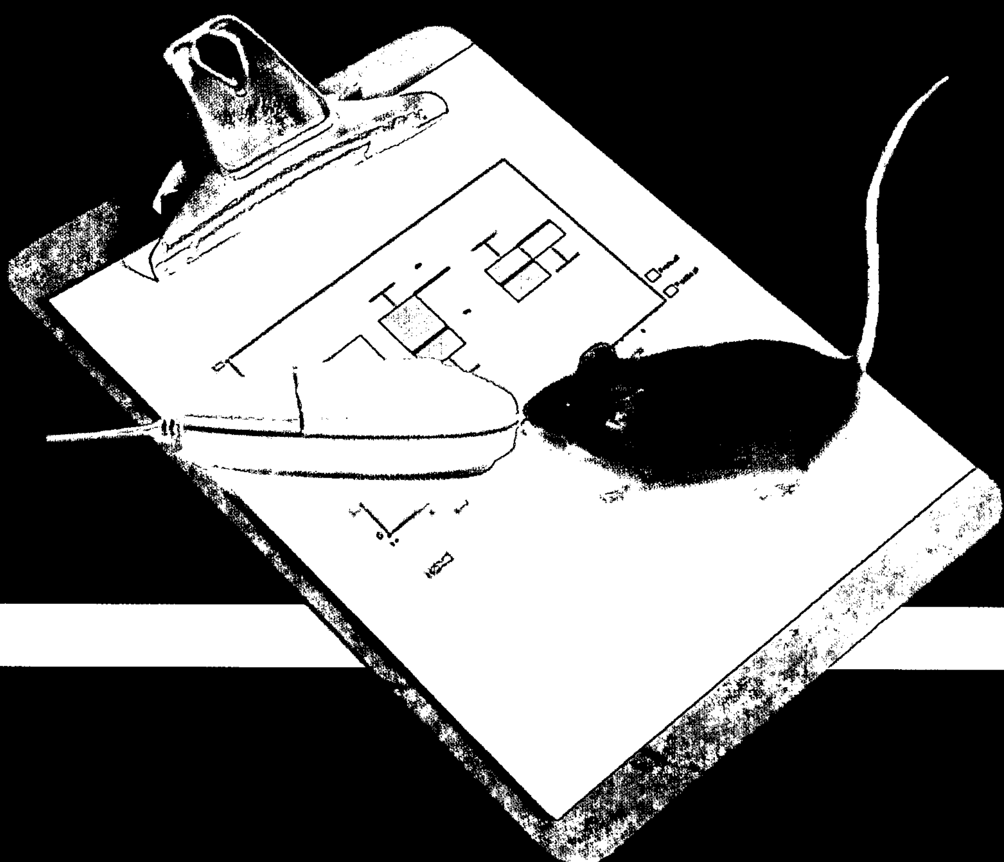

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