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Teaching science

by John R. Staver

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EDUCATIONAL PRACTICES SERIES–17

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Series Preface

This booklet is about teaching science. It has been prepared for inclusion in the Educational Practices Series developed by the International Academy of Education and distributed by the International Bureau of Education and the Academy. As part of its mission, the Academy provides timely syntheses of research on educational topics of international importance. This booklet is the seventeenth in the series on educational practices that generally improve learning.

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John Staver thanks Luciana de Oliveira, Nicole Hands, and Cecilia Hernandez for their comments and suggestions on an earlier draft of this booklet. Luciana de Oliveira, a native of Brazil, is assistant professor of literacy and language education at Purdue University. Her research focuses on English learners' development of academic literacy in the content areas, second language writing, diversity and equity in teacher education, and nonnative English speakers as language teachers. Nicole Hands taught middle school English language learners and now works in Purdue University's Science Outreach Program. Cecilia Hernandez taught science to eighth graders in rural west Texas; she is a doctoral student in science education at Kansas State University.

The officers of the International Academy of Education are aware that this booklet is based on research carried out primarily in economically advanced countries. The booklet, however, focuses on aspects of reading and instruction that are universal. The practices presented here are likely to be generally applicable throughout the world. Indeed, they might be especially useful in countries that are currently less developed economically. Even so, the principles should be assessed with reference to local conditions, and adapted accordingly. In any educational setting or cultural context, suggestions or guidelines for practice require sensitive and sensible application, and continuing evaluation.

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Introduction

What is science? Science is a way of knowing, a method of learning about nature. Rooted in common sense, its formal, systematic method is called scientific inquiry. In doing scientific inquiry, scientists use a variety of empirical approaches, techniques, and procedures to collect data from nature, examine and analyze that data, and construct knowledge based on it. This knowledge relates to living organisms, non-living matter, energy, and events that occur naturally. To analyze data scientists often, but not always, use mathematics, and they always apply logical arguments that obey strict empirical standards and healthy skepticism.

The product of scientific inquiry is the body of scientific knowledge. Scientific knowledge takes four forms: hypotheses, facts, laws, and theories. Hypotheses are tentative statements about relationships between variables in nature. Long ago the rotation of the earth on its axis and the orbit of the earth about the sun were hypotheses. Over time and through scientific inquiry, hypotheses may become facts. Facts are scientific observations that have been tested and confirmed repeatedly. The motion of a Foucault pendulum over a 24-hour period documents Earth's rotation on its axis. Observations of the shifting shadows of fixed objects over several weeks and the changing hours of daylight and darkness over several months help document Earth's revolution around the sun. Earth's rotation and orbit are now scientific facts. Hypotheses may also become laws. Laws describe the behaviour of specific aspects of nature under specific conditions. Boyle's Law states that the volume (one property) of an ideal gas varies inversely (behaviour) with its pressure (second property) when the temperature (third property) of the gas is constant (specific condition). Theories are explanations about broad aspects of nature that encompass large numbers of hypotheses, facts, laws, and events. These explanations are well tested and valued for their ability to predict new scientific knowledge and produce practical benefits. Evolutionary theory explains the extensive diversity across living organisms as well as the underlying unity. Scientists in health, agriculture, and industry use evolution to develop new medicines, hybrid crops, and new molecules that enhance the performance of systems and benefit individuals and societies.

Education in science serves three purposes. First, it prepares students to study science at higher levels of education. Second, it prepares students to enter the workforce, pursue occupations, and take up careers. Third, it prepares them to become more scientifically literate citizens. The relative priority and alignment of these three purposes varies extensively across countries and cultures. Regardless of the setting, a sound education in science emphasizes that science is both a way of knowing and a body of knowledge; it also emphasizes integrating scientific inquiry with scientific knowledge.

Much is known about teaching science effectively to learners of all ages. This knowledge comes from research and scholarship conducted in both developed and developing countries. The principles listed in this booklet are built on this extensive and growing body of research.

John R. Staver

References

1. Abell & Lederman, 2007; Bransford, Brown, & Cocking, 1999; Gauch, 2003; National Academy of Sciences, 1998; National Academy of Sciences & Institute of Medicine, 2007; National Research Council, 1996, 2000, 2007; Project 2061, 1990.

1. Teaching as a purposeful means to an end

Think of science teaching as a purposeful means to an important end: student learning.

Research findings

All teachers hold personal beliefs and dispositions about teaching, learning, and learners. Some teachers believe their responsibility is to teach the material, and the students' responsibility is to learn what is taught. If students struggle or fail to learn, the responsibility rests only with the students. Such a viewpoint runs counter to principle #1, stated in the box above. Effective science teaching is a purposeful means to an important end, not the end itself. Teachers who embrace principle #1 accept some measure of responsibility for their students' struggles and failure to learn. The degree of responsibility they accept depends on the students' level of effort to learn. If students and teacher both work hard, the teacher should accept a large portion of responsibility when students encounter difficulties or fail to learn. The teacher should also be able to modify instruction to help struggling and failing students improve. The practical applications listed below describe specific expressions of the beliefs and dispositions of effective science teachers. Principles 2–8 and their practical applications specify actions of effective science teachers who view student learning as the end goal and teaching as a purposeful means to help all students learn.

Practical applications

Effective science teachers believe and act in these ways:

- Respect and accept the unique perceptions of individual learners.
- Reflect on and consider learners' prior knowledge and interests when selecting and using specific teaching strategies and techniques.
- Believe that all students can and will learn.
- Create a challenging, but non-threatening, learning environment.
- Commit to the learning and intellectual growth of all learners.
- View oneself as capable, dependable, and generally positive.
- Believe that one can teach effectively and that effective teaching will lead to positive learning outcomes.

Suggested readings: Combs, 1999; Cruickshank, Jenkins, & Metcalf, 2006; Wang, Haertel, & Walberg, 1993.

2. Core scientific ideas

Concentrate on the core scientific ideas that have the greatest importance.

Research findings

Teachers have long taught science as a sequence of lectures and reading assignments on its body of knowledge. If laboratory activities are included, they focus only on the development of lab skills and techniques, not on constructing new scientific ideas through inquiry. Such teaching contradicts principle #2 and falls short of preparing students for advanced study, for careers, and for a future as scientifically literate citizens. Today's students live in a world full of the products of scientific inquiry and engineering development. When students complete their formal schooling, they will enter a world filled with products that do not exist today—products that will be the result of scientific inquiry and engineering development. Today's students must learn how to do scientific inquiry and use scientific information to make decisions that will affect their personal lives, careers, and societies. To prepare students to live and work in tomorrow's world, science teachers must make room for scientific inquiry by decreasing their emphasis on teaching science as a sequence of lectures and reading assignments on the body of scientific knowledge. In addition, teachers must greatly decrease their coverage of non-core scientific knowledge. While doing so, they must retain the core knowledge in the scientific disciplines and increase their emphasis on scientific inquiry as a core part of science content and as a method of instruction.

Practical applications

Effective science teachers work together and align their work with appropriate science standards (if they are available). In doing so, they use these approaches:

- Identify the core ideas of their science discipline across all grade levels.
- Decide which core scientific ideas will be taught in the early, middle, and upper grades.
- Outline how core scientific ideas that are introduced in the early grades will be developed further in the middle and upper grades.
- Select science curricula for the early, middle, and upper grades that focus on core scientific knowledge and include scientific inquiry as part of the core of scientific knowledge.

- Select science curricula for the early, middle, and upper grades that emphasize scientific inquiry as a method of teaching.
- Maintain a high level of consistency among the goals and objectives, instruction, and assessment of each lesson, unit of instruction, course, and programme.

Suggested readings: National Research Council, 1999; Project 2061, 1993, 2000, 2001, 2007.

3. Deep scientific understanding

Promote deep scientific understanding through teaching that mirrors the nature and characteristics of inquiry in science, the values of science, and the body of scientific knowledge.

Research findings

Deep understanding in science goes well beyond memorization of isolated facts and concepts. Deep scientific understanding includes a coherent system of facts, concepts, scientific inquiry, and strong problem-solving ability. Emphasizing scientific inquiry and problem solving promotes deep understanding of science. Defined broadly, a problem exists when a learner stands on one side of a gap and has little or no idea how to get to the other side. Problem solving, then, becomes what learners do when they have little or no idea what to do. In contrast, an exercise is a task that learners have an immediate, excellent idea how to complete, perhaps because their teacher gave advance directions on how to complete it. At present, school science contains too many exercises and too few problems.

Scientists pose and solve problems through scientific inquiry. Research on problem solving identifies the first step as the most important. Students must be able to describe or represent the gap to be crossed in a viable, physical way. This involves translating the problem as presented into a form that is meaningful to the problem solver. This initial step is largely conceptual, reflective, and qualitative, even when the problem and the problem-solving process depend largely on mathematics. For example, the problem solver might represent the problem as a picture or diagram, or separate a complex problem into smaller parts.

Effective problem solvers construct representations of the gap more correctly and precisely than do ineffective problem solvers. Effective problem solvers exhibit a more organized, relevant knowledge base than do ineffective problem solvers. Effective problem solvers spend more time on representing the gap and planning solutions to the problem than do ineffective problem solvers. Effective and ineffective problem solvers make similar numbers of errors, but effective problem solvers have better checking strategies to identify and correct errors. Students can become more effective problem solvers through science teaching that emphasizes scientific problem solving and deemphasizes exercises.

Practical applications

Effective science teachers use these techniques to promote deep scientific understanding:

- To determine if tasks are problems or exercises for students, ask all students if they have a good-to-excellent idea or little-to-no idea how to do specific tasks.
- Organize cooperative student groups that reflect intellectual, gender, and cultural diversity; have members of the group share and discuss their representations of the gap and proposed solution strategies.
- Use guided-inquiry teaching strategies (e.g., Learning Cycle, 5-E Instructional Model) that lead learners to continue developing and modifying their knowledge.
- Aim problem-solving instruction slightly beyond what students can do alone but within the boundaries of what they can do with assistance from others.
- Use science concepts and processes as contexts for students to write persuasive essays, engage in oral discussions, connect data with scientific theories, and solve problems requiring mathematical reasoning.
- Design discussions and negotiations among students as on-going learning experiences.
- Provide opportunities for students to claim ownership of their learning.

Suggested readings: Abell & Lederman, 2007; Bransford, Brown, & Cocking, 1999; Bybee, 1997; Driscoll, 2005; Hayes, 1981; National Research Council, 2005; Vygotsky, 1978.

4. Complexity of learning

When designing and teaching science lessons, consider the complex interaction between learners' biological maturation, prior knowledge and experience, and reasoning abilities, so the lessons challenge but do not overwhelm learners' cognitive capabilities.

Research findings

Learning relies on a complex synthesis of biological maturation, prior knowledge and experience, reasoning ability, and instruction. Students' learning capabilities at any age depend heavily on their prior knowledge and experiences, which can help or hinder them from learning something new—or have no effect. This extensive range of knowledge and experience stems from learners' socioeconomic status, gender, ethnicity, culture, native language, and other factors. Different learners require different kinds of explicit instructional support and guidance to understand and do scientific inquiry and to understand the body of scientific knowledge. For example, scientific inquiry occurs in a social setting, where scientists collect, analyze, discuss, and evaluate evidence to test hypotheses and develop scientific explanations together. This is scientific argument. Children's daily experiences with argument are quite different; children resolve arguments based on authority, social status, and physical size. Science teachers must discern the roots of students' struggles to learn and simultaneously provide instruction that is challenging but not overwhelming. Asking questions during instruction is an effective strategy for assessing students' difficulties.

Practical applications

Effective science teachers use these techniques in response to the complexity of learning:

- Give a pretest before starting a unit of instruction; use the results to learn what students know and do not know, and to plan appropriate lessons.
- Use concrete, manipulative materials and familiar events to help students directly experience scientific phenomena and to encourage their active construction of abstract concepts.

- Ask a blend of high-level, low-level, open-ended, and closed-ended questions to activate students' thinking.
- Wait at least three seconds after asking a question before rephrasing it.
- Wait at least three seconds following a student's response to a question before continuing.
- Delay including abstract science concepts with young children if these concepts cannot be introduced with concrete materials and familiar experiences.
- Aim the level of instruction slightly beyond the capabilities of individual learners but within the capabilities of groups of learners.

Suggested readings: Driscoll, 2005; National Research Council, 2001, 2005; Rowe, 1974a, 1974b; Tobin, 1987; Vygotsky, 1978.

5. Active construction of scientific knowledge

Teach with strategies and techniques that help learners become active thinkers.

Research findings

Modern learning theory describes learning as an active, internal process of constructing new understandings. In some instances, a newly constructed idea fits easily into the structure of existing understanding. In other cases, the construction of new understanding catalyzes substantial revision of existing knowledge into a new, more coherent framework. In still other instances, new and old ideas conflict but are retained and used separately. Learning is also a social and cultural process. Individual learners' interactions with their peers are important to each learner's active construction process and the group process. The construction of deep scientific knowledge results from actively practicing science in structured learning environments. Learning environments should support students' active construction of knowledge. Teachers should employ teaching strategies that help learners recognize conflicts and inconsistencies in their thinking, as these experiences catalyze the construction of new, more coherent knowledge.

Practical applications

Effective science teachers use these approaches to ensure that students are actively constructing their learning:

- Present science as a process of constructing and empirically testing models for their ability to explain and predict.
- Devote time to diagnosing learners' alternative conceptions.
- Employ a repertoire of teaching approaches that range from open and guided inquiry to direct instruction.
- Use teaching strategies and assessment formats that are consistent with the goals of the lesson.
- Use teaching strategies that help learners become aware of inconsistencies in their thinking.
- Use teaching strategies that raise students' awareness of how they construct knowledge together and as individuals.

- Employ discrepant events to engage learners with concrete phenomena, activate their interest, and help them become aware of the conflicts between their thinking and accepted scientific concepts.
- When determining the order in which to introduce science concepts in a given domain, consider the ways those concepts are interdependent.
- Use teaching strategies that include familiar analogies, metaphors, and physical models to guide learners toward accepted scientific concepts.
- Adapt available curriculum materials and teaching strategies to fit the diverse needs of all students.
- Organize cooperative student learning groups that reflect intellectual, gender, and cultural diversity.
- Conduct frequent assessments as a seamless part of teaching and use the results to modify instructional experiences for groups and individual learners.

Suggested readings: Abell & Lederman, 2007; Carin, Bass, & Contant, 2005; Cruickshank, Jenkins, & Metcalf, 2006; Driscoll, 2005; National Research Council, 2001, 2005, 2007; Staver, 1998.

6. Science content and students' interests

Connect science content with students' interests and personal lives, with societal issues, and with other school subjects.

Research findings

Learning is a purposeful, internal, mental process. Teachers can monitor learning by observing and gathering data on changes in students' actual behaviour or potential performance. Motivation drives the process of starting and continuing learning. Relevance refers to activities that give students satisfaction and meet their needs, including the chance to achieve personal learning goals. In order to capture students' attention and activate their motivation to learn, teachers must consider the relevance of each topic. Then they can connect science with students' interests, personal lives, societal issues, cultural backgrounds, and other school subjects. Cognitive learning theory emphasizes the importance of learning something new by relating it to things that are already meaningful and familiar. Science teachers must remember that their own intrinsic motivation to learn science is likely not shared by many of their students, whose motivation is more likely activated instrumentally, by connecting science to things that are already familiar and important to them.

Practical applications

Effective science teachers use these techniques to connect content with student interests:

- Connect science concepts and instruction explicitly to learners' personal experiences.
- Use specific examples, analogies, and metaphors.
- Plan lessons to emphasize themes of science, technology, and society.
- Have students organize data into diagrams, tables and graphs.
- Have students use data in tables and graphs (bar, line, histogram) to identify patterns and make predictions.
- Have students use mathematical operations, fractions, decimals and percentages to calculate results of investigations.

- Have students read passages in science texts and trade books and identify major and minor ideas, summarize what they have read, and make predictions.
- Have students develop and role play scenes in which they use scientific thinking or play the roles of scientists.

Suggested readings: Abell & Lederman, 2007; Carin, Bass, & Contant, 2005; Cruickshank, Jenkins, & Metcalf, 2006; National Research Council, 1996; Project 2061, 1990, 1993.

7. Expectations for learning

For all students, set high expectations for learning.

Research findings

Teachers' expectations of how much and how well their students will learn directly influence that learning. Teachers should set high learning expectations for all students—and encourage them to set high expectations for their own learning. Teachers express their expectations for and beliefs about their students through both their nonverbal and verbal behaviours. Students who are believed to be high-ability learners receive more positive nonverbal feedback from teachers such as smiling and eye contact. Students believed to be low-ability learners are asked fewer and less challenging questions; they also get less feedback, less time to respond, and less praise. When instruction is tracked, perceived low-ability students often receive less challenging content and are given more assignments that require rote memorization and drill-and-practice activities. Teachers' overly high expectations for high-ability students, however, can lead to inaction when those learners do need corrective action in order to achieve.

Students are sensitive to teachers' beliefs about them. In cultures where low achievement is attributed to low ability and ability is believed to be unalterable, low-ability students often come to believe that their performance will not change regardless of their level of effort. In cultures where students' level of work and effort is considered directly related to their learning, high expectations for all students lead to higher achievement through more work and effort by students of all abilities.

Practical applications

Effective science teachers use these strategies to set and maintain high expectations:

- Monitor and analyze students' work and take corrective individual and group action as needed.
- Help students believe in their ability to learn effectively and to raise their awareness of positive outcomes as a result.
- Help students view themselves as capable learners.
- Build learners' confidence by breaking difficult tasks into smaller steps that they view as more manageable and achievable.

- Provide assistance but do not do tasks for students.
- Give learners a reasonable level of control over their learning.
- Help learners become aware that their own efforts, strategies, and persistence are important to their successful learning.
- Help learners experience the satisfaction of successful learning.

Suggested readings: Carin, Bass, & Contant, 2005; Cruickshank, Jenkins, & Metcalf, 2006; National Research Council, 2001.

8. Students' anxieties and conflicts

Use teaching strategies that lessen students' potential anxieties and perceived conflicts when teaching scientific ideas that may be controversial for learners, even though they are not controversial among scientists.

Research findings

Scientists know that core scientific ideas have been well tested and are not controversial. Students, however, may perceive conflicts between their prior knowledge and some core scientific ideas. Evolution is an example. Teachers should take the viewpoint that the goal of effective science teaching is to have students understand, not to have them believe. When teaching evolution, teachers should deemphasize their use of words such as "true" and "believe". Students' prior knowledge of truth and belief is often based on their religious views, in which truth is absolute, ultimate, and unchanging, and to believe means to think of something as absolutely true. Teachers should emphasize that scientists accept evolution on the basis of several independent lines of scientific evidence that have developed over nearly 150 years. Teachers should take an instrumental or pragmatic stance, emphasizing that evolution works; in fact, it is an excellent tool for problem-solving. Evolution explains natural phenomena, predicts new natural phenomena, and represents the scientific foundation for the many ways that nature provides benefits to humans in health, agriculture, and industry. Teachers should emphasize that scientific knowledge is based on empirical evidence and is always subject to revision based on new scientific discoveries.

Practical applications

Effective science teachers use these strategies to address students' anxieties and conflicts:

- Be sensitive to students' verbal and nonverbal behaviour when teaching a unit that students may perceive as containing controversial ideas.
- Clarify the difference between understanding and believing.
- Use peer-group discussions to help students become aware of other students' thoughts about the concept.
- Avoid using words such as 'true' and 'believe' in reference to science concepts.

- Emphasize the explanatory power and predictive ability of a concept.
- Encourage students to think about concepts as tools for solving scientific problems.
- Point out how a concept or theory may benefit individuals, society, and the environment.

Suggested readings: Anderson, 2007; Bybee, 2004; National Academy of Sciences & Institute of Medicine, 2007; National Research Council, 2007; Scharmann, 1990, 1993, 1994, 2005; Scharmann & Harris, 1992; Staver, 2003.

9. Conclusion

Teaching science effectively is difficult but rewarding work. The difficulty stems from two sources. First, students in most science classes bring a wide range of prior knowledge, experiences, reasoning, and interests. Second, teachers must integrate the core body of scientific knowledge and scientific inquiry in a way that does justice to both the aspects of science and their integration. Teachers' rewards are rooted in knowing that students have learned as a result of their effectiveness as teachers. The key is principle #1: Teaching is a purposeful means to help students learn. When students work hard but fail to learn, the teacher must accept a large part of the responsibility. Teachers must embrace the view that effective teaching means constantly being aware of and attending to students' struggles to learn science and continually adjusting their teaching strategies and techniques to help students work through difficulties. In doing so, teachers should set high learning expectations, focus on core scientific ideas, and aim for deep, integrated understanding of scientific inquiry and the core body of scientific knowledge. To help students reach teachers' aims and expectations, teachers must understand how learners actively construct new knowledge, as well as the complexity of the learning process, the importance of students' interests, and students' potential anxieties and conflicts with science concepts. Another reward for teachers is knowing that their students are experiencing a sound education in science, one that prepares them for advanced studies and for their occupations and careers, and that also helps students recognize the importance, usefulness, and value of science in their personal lives.

An old proverb says that given a fish, one can eat for a day; taught to fish, one can eat for a lifetime. Think of effective science teaching as teaching learners to fish. Once learners come to understand and use scientific thinking to learn more about the world around them, they have become fishers with a lifetime thirst for knowledge and the skills to seek and learn on their own.

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The IBE was founded in Geneva, Switzerland, as a private, non-governmental organization in 1925. In 1929, under new statutes, it became the first intergovernmental organization in the field of education. Since 1969 the Institute has been an integral part of UNESCO while retaining wide intellectual and functional autonomy.

The mission of the IBE is to function as an international centre for the development of contents and methods of education. It builds networks to share expertise on, and foster national capacities for curriculum change and development in all the regions of the world. It aims to introduce modern approaches in curriculum design and implementation, improve practical skills, and foster international dialogue on educational policies.

The IBE contributes to the attainment of quality Education for All (EFA) mainly through: (a) developing and facilitating a worldwide network and a Community of Practice of curriculum specialists; (b) providing advisory services and technical assistance in response to specific demands for curriculum reform or development; (c) collecting, producing and giving access to a wide range of information resources and materials on education systems, curricula and curriculum development processes from around the world, including online databases (such as *World Data on Education*), thematic studies, publications (such as *Prospects*, the quarterly review of education), national reports, as well as curriculum materials and approaches for HIV & AIDS education at primary and secondary levels through the HIV & AIDS Clearinghouse; and (d) facilitating and fostering international dialogue on educational policies, strategies and reforms among decision-makers and other stakeholders, in particular through the International Conference on Education—organized by the IBE since 1934—, which can be considered one of the main forums for developing world-level policy dialogue between Ministers of Education.

The IBE is governed by a Council composed of representatives of twenty-eight Member States elected by the General Conference of UNESCO. The IBE is proud to be associated with the work of the International Academy of Education and publishes this material in its capacity as a Clearinghouse promoting the exchange of information on educational practices.

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