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A Framework for Assessing Student Understanding in Science

ASSESSMENT BASED ON SIX DOMAINS OF SCIENCE

When humans use scientific knowledge and technology, global awareness becomes critical for environmental protection. As the American Association for the Advancement of Science (1990) stated in *Science for All Americans*,

> What the future holds in store for individual human beings, the nation, and the world depends largely on the wisdom with which humans use science and technology. But that, in turn, depends on the character, distribution, and effectiveness of the education that people receive. (p. vi)

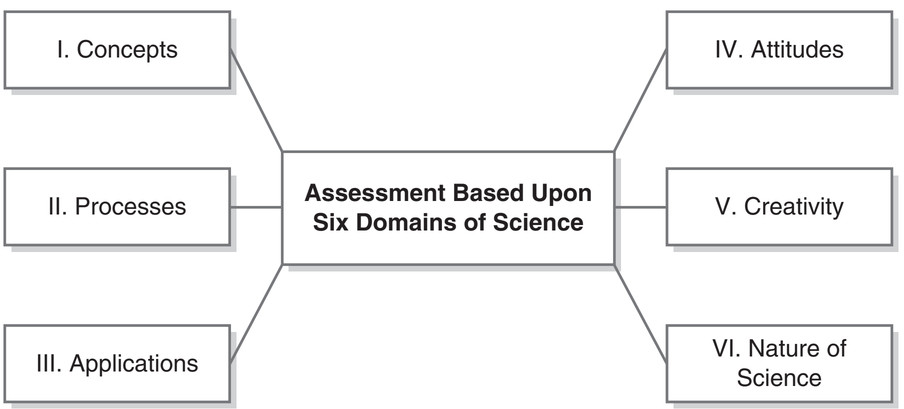
Accordingly, scientific literacy has become a major goal of science education. Although there is no consensus regarding what kinds of science content are necessary for scientific literacy, a scientifically literate person is believed to be one who appreciates the strengths and limitations of science and who knows how to use scientific knowledge and scientific ways of thinking in order to live a better life and make rational social decisions.

Learning that fosters scientific literacy should promote development in the following areas:

- Students' inquiry skills and abilities
- Students' abilities to apply what is learned to new contexts
- Students' content and conceptual understanding
- Students' understanding of the nature of science

Yager and McCormack (1989) proposed that science had been viewed as a body of knowledge consisting of facts, figures, and theories, and this led to science instruction characterized by presentations of factual information. Yager and McCormack believed that science education that stressed what they called the "Knowing and Understanding" domain limited students in developing the level of scientific literacy demanded by the needs of society and the world. They first proposed that science education might be viewed in the context of five domains but later expanded these to six domains when they included the nature of science. As shown in Figure 1.1, an assessment framework for science learning and experiences to promote science literacy can be organized around six domains.

Figure 1.1 The Six Domains of Science



Yager (1987) noted that what was typical of science tests were questions that assessed factual, recall types of knowledge, and with grant-funded projects such as the NSF-funded Iowa Chautauqua project, he emphasized and promoted assessment in all six domains. These expectations to assess more broadly present challenges in identifying and creating assessments that measure the components in the six domains. Table 1.1 shows the foci of the six domains. If the domains are intended to support and anchor science, then instruction and experiences that provide learning opportunities in these areas are necessary for student understanding in science.

Table 1.1 What Characterizes Each of the Six Domains?

Science Domain	*Domain Foci*
I. Concepts (knowing and understanding)	Scientific information—facts, concepts, laws, hypotheses, and theories accepted by the scientific community
II. Processes (exploring and discovering)	Processes of science, how scientists work and think
III. Applications (using and applying)	Applications of what is learned to do science, connections to everyday life; informed decision making
IV. Attitudes (feeling and valuing)	Attitudes, sensitivity, societal issues and impacts
V. Creativity (imagining and creating)	Idea generation, designing, problem solving
VI. Nature of Science (the scientific endeavor)	History and philosophy of science; how science progresses and science knowledge and understanding develop

I. CONCEPTUAL DOMAIN

What Research Says About the Conceptual Domain

Science concepts are central to science instruction, and students' understanding of these concepts is crucial to successful teaching and learning. Millar (1989) noted that without an understanding of science concepts it would be nearly impossible for students to follow much of the public discussion of scientific results or public policy issues pertaining to science and technology. According to Thagard (1992), conceptual systems are primarily structured via either *kind* (or *is-a*) hierarchies (e.g., Tweety is a canary, which is a kind of bird, which is a kind of animal, which is a kind of organism) or *part-whole* hierarchies (e.g., a toe is part of a foot, which is part of a leg, which is part of a body). If a basic goal of science education is to help students construct an understanding of the natural world, then students' prior knowledge should be the starting point for instruction.

Assessment enters the field of view to help make determinations on where students are with respect to conceptual understanding. Students should have concrete experience with concepts before moving to abstractions, and they need opportunities to try and to do, not just to read about science. The evidence that science concepts have been learned can be seen most clearly when students can use concepts in a real-life or real-world situation (National Science Teachers Association [NSTA], 1982).

Science in the classroom has been viewed and practiced for decades as a body of knowledge or facts to be learned or absorbed by students. Classically, this occurs via the memorization of facts and concepts from a textbook. Science facts are clearly important, but to memorize facts as if their acquisition is the sole purpose of science education violates the spirit and nature of science. This issue will be addressed further in Section VI, Nature of Science Domain.

What the Concept Domain Includes

Facts, laws or principles, theories, and the internalized knowledge held by students all fall under the umbrella of the concept domain (Yager & McCormack, 1989). These are the currently accepted scientific constructs related to all of the sciences, and students may best learn these concepts through a curriculum that is conceptually sequenced for developing student understanding. Students must also experience the curriculum from conceptually sound models of assessment and instruction. Science learning should promote conceptual linkages instead of a concepts-in-isolation approach. Concept mastery is an essential aim . . . but only when a meaningful context has been established. Both *Benchmarks for Science Literacy* (American Association for the Advancement of Science [AAAS], 1993) and the *National Science Education Standards* (National Research Council [NRC], 1996) provide recommendations about content, concepts, and contexts. The American Association for the Advancement of Science (AAAS) has also published two atlases of science literacy where concept strand maps show connections across grade bands (AAAS, 2001, 2007).

II. PROCESS DOMAIN

What Research Says About the Process Domain

Science processes, often designated as *inquiry skills*, are embodied in the terms *exploring* and *investigating*. In science, the investigative processes require hands-on and minds-on activities, laboratory inquiries, and experiments that provide approaches for helping students understand scientific concepts. A study conducted by Shavelson, Baxter, and Pine (1992) found that students with experience in hands-on activities could reliably note their own progress in laboratory activities. More important, these kinds of inquiry skills are also necessary for dealing with everyday life and play a role in the development of an understanding of the natural world (Aikenhead, 1979). The contexts in which the inquiries are set are important in helping students connect the inquiry skills to their personal experiences so that students do not see the processes used in doing science as entities used *only* in science. The application of process skills in a variety of contexts also supports the development of an understanding of the nature of science. Knowledge of the process of constructing and communicating new scientific representations has the potential to yield important insights for science education (Nersessian, 1989).

What the Process Domain Includes

The process domain includes the 13 processes identified by the American Association for the Advancement of Science (1968), which provided the framework for the program in *Science: A Process Approach*. These are the generally accepted processes that scientists use as they accomplish their work, and slight variations in how these are categorized do exist. The abilities to use these process skills can be the target for instruction and assessment, but the identification of separate and distinct processes does not mean that they always occur in definable or identifiable ways. Scientists and students may use several of the science process skills in concert, and these skills may be employed during scientific investigations in ways not expected or predicted by anyone observing the investigative process. These processes and skills are embedded in knowing, doing, and thinking in science.

Process Skills Used in Science

- Observing
- Using space and time relationships
- Classifying, grouping, and organizing
- Using numbers and quantifying
- Measuring
- Communicating
- Inferring
- Predicting
- Identifying and controlling variables
- Interpreting data
- Formulating hypotheses
- Defining operationally
- Experimenting

A Brief Note on How Observation Is Theory Laden

The process of making observations may be influenced by what a person already knows about the subject or object of the observation. The prior knowledge and the conceptual framework that already exist in a person's schema influence the nature and depth of observation. This framework may or may not be accurate, but observations are made within the context of this framework. What a person can see depends on what he or she believes, and the observation is therefore theory laden (Abimbola, 1983). Personal viewpoints and creativity also play roles in any investigation, and this brings the implication that the beginning point for investigation should be based on student ideas and questions. Such ideas come from students' prior scientific knowledge, deduction, or even personal guesses and creativity. This idea that observation is theory laden may not have been overtly discussed or considered by students.

A Brief Note About Confirmatory Laboratory Work

Student laboratories and experiments can become exercises in finding the one right answer; whereas learning a protocol or procedure is often necessary in science, student experiences should move beyond this. Laboratories and investigations should provide opportunities for students to test their own ideas so that they use and develop their abilities in the process domain. Student-generated ideas can serve as the basis for the question or hypothesis that typically precedes any investigation.

A science teacher does need to play a role as the advocate of current "public concepts" (the currently accepted scientific thought) to challenge students' "private thought" (Matthews, 1994) or to persuade (Kuhn, 1962) or convince a student to appreciate the current, prevalent interpretation or explanation of natural phenomena. Group discussion for an investigation may produce the same persuading effect (Johnson & Johnson, 1983). Students who understand the role of process skills in scientific investigations may be more likely to see science as a career that has the potential to be fun and creative.

III. APPLICATION DOMAIN

What Research Says About the Application Domain

A key element in the application domain is the determination of the extent to which students can transfer and effectively use what they have learned to a new situation, especially one in their own daily lives (Grönlund, 1988). Students must demonstrate that they not only grasp the meaning of the information and processes but that they can also make applications to concrete situations that are new to them. The application domain is important because it involves students using concepts and processes not only in a familiar context but in addressing new problems. Students who can apply what they have learned to new situations provide evidence that they have an understanding of a concept.

Two major arenas where students use applications are in school and in daily life. In school, application often involves problem solving or learning new material by using knowledge and skills acquired in previous studies. In daily life, the crucial factor appears to be the ability to choose the concepts and skills pertinent and relevant for dealing with novel situations. In helping students make applications and connections among science, technology, and their personal lives, the use of current social and technological issues can assist students in seeing the need for the integration of knowledge and skills. Beginning science learning based on students' concerns in the so-called real world may be a way to diminish the learning gap between the world of school science experiences and their personal societal and technological experiences (Yager & McCormack, 1989). An issues-based approach to science learning can serve as a vehicle for engaging students in learning that is local, personal, and relevant.

Attributes of the Application Domain

- Use of critical thinking
- Use of open-ended questions
- Use of scientific processes in solving problems that occur in daily life
- Abilities to make intradisciplinary connections—integration of the sciences
- Abilities to make interdisciplinary connections—integration of science with other subjects
- Decision making related to personal health, nutrition, and lifestyle based on knowledge of scientific concepts rather than on hearsay or emotions
- Understanding and evaluation of mass media reports on scientific developments
- Application of science concepts and skills to technological problems
- Understanding of scientific and technological principles involved in common technological devices

A Brief Note About Science, Technology, and Society

Science-Technology-Society (STS) is an approach characterized by a focus on the integration of science and technology (Yager & Roy, 1993). With the STS approach, local issues provide a science context that has greater student relevancy, and the students learn concepts through activities and community action. With STS, the area in which students live can serve as the venue in which to learn science. If students live in an area with wetlands, science can be experienced in the context of the wetlands. Students might study water and habitat quality, and they could develop environmental impact studies. What are the potential benefits or detriments that exist for the community if, for example, a land developer changes the habitat to build homes needed to support economic development? In an urban setting, students might study the need to add green spaces. Students become involved in resolving local issues and proposing solutions, and this approach also pushes students to seek current information from a variety of sources and experts in various fields of study. With technology, online collaboration among students generates even greater numbers of possibilities to examine issues.

IV. ATTITUDE DOMAIN

What Research Says About the Attitude Domain

How many times have you heard people say that they were never good at science, mathematics, or some other area of study? How important is attitude anyway? Felker (1974) found that when students were induced to make positive statements about themselves, they attained more positive attitudes about themselves. Page (1958) indicated that teachers who reflected an active and personal interest in their students' progress were more likely to be successful in enhancing the personal confidence levels of students.

Attitude is very broadly used in discussing issues in science education and is often used in various contexts. Two general categories that are distinguishable are (a) attitude toward science (i.e., interest in science, attitude toward scientists, and attitude toward social responsibility in science) and (b) scientific attitude (i.e., open-mindedness, honesty, or skepticism) (Gardner, 1975). Interest in science tends to decline as students experience more science classes and progress through school. This is especially true in the middle school years when enrollment in science classes declines. Science educators need to work to retain student interest in science and need to consider changing both instruction and assessment practices to be more student-centered in order to promote ongoing interest.

The positive "I can" attitude and "I enjoy" feelings may enhance students' efforts to seek answers for their own problems and lessen their reliance on others. Students should be able to solve problems with greater independence without parent or teacher intervention. Statements such as, "Don't tell me the answer," or "I can figure it out all by myself," indicate a growing autonomy. The end result of this self-directed growth could very well be self-acceptance and responsibility for lifelong learning.

Attitude Domain Attributes

The attitude domain calls for experiences that support

- exploration of human emotions,
- expression of personal feelings in constructive ways,
- decision making about personal values,
- decision making about social and environmental issues,
- development of more positive student attitudes toward science in general,
- development of positive attitudes toward oneself (an "I can do it" attitude), and
- development of sensitivity to and respect for the feelings of other people.

A Little Attitude Adjustment, According to Charles Swindoll

Although this attitude may seem beyond the scope of a science classroom, consider the words of Charles Swindoll (1994):

> The longer I live the more I realize the impact of attitude on life. Attitude to me is more important than facts. . . . I am convinced that life is 10% what happens to me and 90% how I react to it. And so it is with you. . . . We are in charge of our Attitudes.

V. CREATIVITY DOMAIN

What Research Says About the Creativity Domain

Creativity is integral to science and the scientific process and is used in generating problems and hypotheses and in developing plans of action (Hodson & Reid, 1988). Torrance (1969) defined creativity as the process of becoming sensitive to problems, deficiencies, gaps in knowledge, missing elements, and disharmonies. He also included in his description the identification of the difficulties, the search for solutions, making guesses, or formulating hypotheses about the deficiencies. The testing and retesting of these hypotheses, possibly modifying and retesting them, and finally communicating the results all relate to and rely on the creative process.

Creativity plays an integral role in the many processes of science and in doing science. Creativity is a complex construct, is difficult to assess, and rests very often in what might be called *recognizing it when you see it*. If a science educator wishes to foster a classroom that enhances students' creativity, the classroom should probably become more student-centered. Creativity is fostered and nurtured via richness in experiences. Creativity calls for openness in the classroom, acceptance of ideas, thinking outside of the box, a try-new-things approach, and a so-called go-with-the-flow approach. In fact, Csikszentmihalyi (1990, 1996) used the word *flow* as descriptive of the state in which creativity is turned on in individuals.

Studies have suggested that the work done in the laboratory rests on the ability to manipulate the objects and the instruments used. Three features of laboratory practice make the need for creative abilities paramount. First, scientists and students do not work with the natural world *as it is*; rather, they manipulate the objects of study to make them more accessible for experimentation. Second, investigators do not work with the natural world *where it is* but are instead able to bring those natural objects into an artificial or vicarious setting (e.g., the laboratory, the classroom, on a slide). Third, scientists and students do not need to study an event *only when it happens* but, rather, can cause the event to occur unnaturally when the situation demands it (Knorr-Cetina, 1981). These three characteristics of a laboratory require an imaginative, inventive mind capable of performing these investigations. These aspects of the scientific enterprise are often ignored in the traditional classroom, yet they are integral to science instruction.

Scientific experiences that can push the creative domain are likely to have some of the following attributes.

Creative Domain Attributes

The creative domain calls for experiences that promote

- visualization—production of mental images,
- generation of metaphors,
- divergent thinking,
- imagination,
- novelty—combining objects and ideas in new ways,
- open-ended questioning,
- solving problems and puzzles,
- consideration of alternative viewpoints,
- designing devices and machines,
- generation of unusual ideas,
- multiple modes of communicating results, and
- representation in various ways and modes.

VI. NATURE OF SCIENCE DOMAIN

What Research Says About the Nature of Science Domain

The endeavors undertaken by researchers in their attempts to understand the natural world can promote students' understanding of how science progresses. Science is a human endeavor that relies on reasoning, insight, energy, skill, and creativity (NRC, 1996). Honesty, values, open-mindedness, and what *Benchmarks for Science Literacy* (AAAS, 1993) denotes as *habits of mind* all play roles in scientific ways of knowing. Working with science teachers to develop their understanding of the nature of science is recommended so that they can then provide instruction that promotes their students' understanding of this construct. Preservice or inservice courses that emphasize the nature of science can result in significant gains in teacher scores on instruments designed to measure understanding of this construct (Akindehein, 1988; Barufaldi, Bethel, & Lamb, 1977). Selected journal articles, discussions, activities, curriculum projects, and media can be used to help build understanding in this domain.

In the course of human history, people have developed many interconnected and subsequently validated ideas about the physical, biological, psychological, and social worlds (AAAS, 1990). Successive generations, enabled by these ideas, have achieved more comprehensive and reliable understanding of the human species and the environment. These ideas have been developed through particular ways of observation, thought, experimentation, and validation. These ways are the bases of what is meant by *the nature of science*, and they are reflective of how science differs from other ways of knowing (AAAS, 1990).

How scientific knowledge has developed and the roles scientists have played during the process are two fundamental aspects that are important for students to know. Raising student awareness and developing an understanding of these aspects should be included in science learning. Science itself is dynamic; as witnessed by history, many ideas have come and eventually been replaced or discarded. Many science educators suggest that instruction in a science classroom should reflect the tentative nature of scientific knowledge (Lederman, 1992).

That scientific knowledge is tentative has two facets that should be expressed explicitly when working with students. First, the purpose of science is to develop a systematic knowledge in order to understand how nature behaves. Students should see science as a human endeavor in which scientific knowledge is developed by humans in an attempt to make sense of the world. Accordingly, scientific knowledge is not a truth to be discovered in the natural world but rather a man-made explanation. Second, scientific knowledge can be changed, shifted from one point of view to another, due to external social influences such as politics, economics, and culture (Kuhn, 1962). This suggests that scientific knowledge is not absolutely objective. Therefore, the understanding of the involvement of social factors in scientific development provides another focus for science education.

Science, accompanied by the power of technology, has unique characteristics that affect society. Perhaps no other human activity has ever played such a role in shaping the directions in which societies have moved. The potential to do good is very often offset by the power to cause harm, and long-term outcomes and effects are not always predictable.

An important aspect of the nature of science is related to how scientists think and work in the scientific community. Helping students to understand more of the nature of science can promote deeper understanding of what it means to *do* science. Science is often portrayed as a major intellectual pursuit of truth. Based on that expectation, many people view scientists as a group of people who are more objective and intelligent than others. Students often believe that scientists can solve problems merely based on their scientific knowledge. Science, however, is a human activity that engages real people.

In doing science, scientists often work collaboratively, and given the specializations in science and related areas, a team approach is very often needed to work on problems. Seldom do scientists work in isolation; a laboratory involves teamwork. In order to ask questions and work at finding solutions to problems, scientists must both share information and obtain information from others in their field, and most important, they must reach a consensus by virtue of discussion and persuasion and not on the basis of mere evidence. Peer review is an important component of doing science, and scientists expect to be challenged and to defend the work they have done. The work that scientists do must be replicable so that others can verify the work. Science is also a venture characterized by these competitive elements: being first to report findings, competing for research money, achieving status within the scientific community, and acquiring status for a university.

Science instruction in the classroom should attempt to portray the nature of the discipline—not simply to study the information and interpretation included in the textbook. Views currently held as so-called truths of science have changed and will continue to change throughout time. Therefore, teaching only for the retention of facts without grounding them in real-world experiences will, sooner or later, only result in the loss of these facts from memory. In an attempt to reflect the nature of science, group work, reporting findings, discussion, and reaching consensus are all parameters involved with the nature of science domain.

The Nature of Science Attributes

The nature of science domain calls for experiences that address

- the framing of questions for scientific research;
- the competitive side of scientific research;
- the methodologies used in scientific research;
- the interactions among science, technology, economy, politics, history, sociology, and philosophy;
- the ways in which teams cooperate in scientific research;
- the history of scientific ideas; and
- the ways in which science builds understanding of the natural world.

ASSESSMENT APPROACHES ALIGNED WITH THE SIX DOMAINS

Assessment approaches should include multiple measures of what students know and can do as a result of their learning experiences. The use of a multifaceted assessment approach has the potential to provide a better profile of student understanding in the six domains, and a more holistic assessment approach relates to the whole student (Raizen & Kaser, 1989). Although standardized tests may be valid in measuring knowledge of facts, they may lack validity in measuring higher-level thinking processes, investigation skills, and practical reasoning (Aikenhead, 1973; Champagne & Newell, 1992). This is not to say that standardized tests cannot and do not measure higher-level thinking processes. The deeper issue involved is one of having the assessments align with instruction and intended student outcomes.