Goals, Guidelines, and Standards for Student Scientific Investigations

iNACOL
International Association for K-12 Online Learning

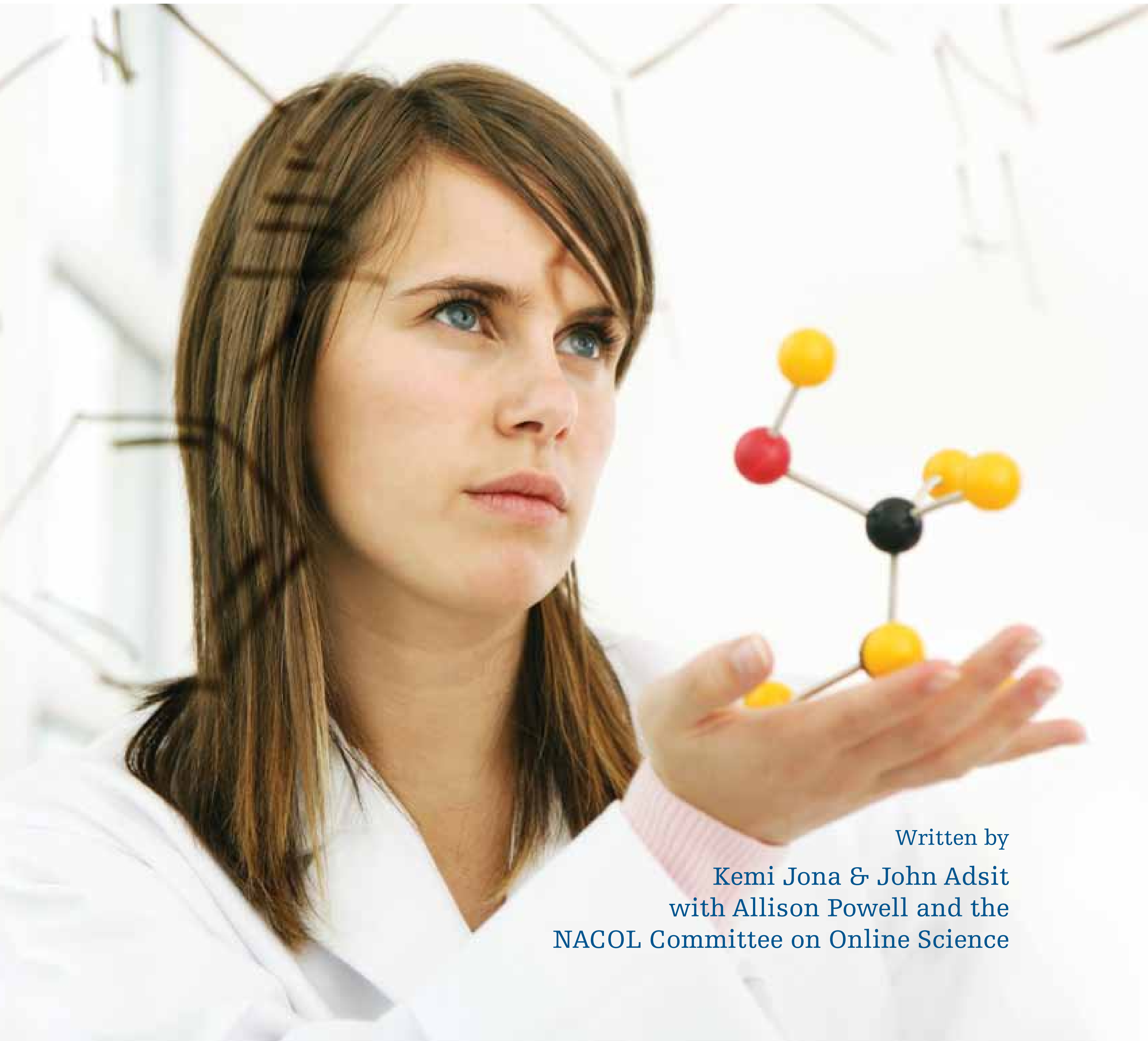

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Table of Contents

Goals, Guidelines, and Standards for Student Scientific Investigations

Introduction

This publication is intended to provide a set of quality guidelines for developing and evaluating student scientific investigations and surrounding course content that are parts of courses (or other learning experiences) delivered online at a distance from the instructor and a traditional science classroom[1]. To be inclusive of the range of approaches that are possible, we adopt the term 'student scientific investigations' rather than 'laboratory.' This term is in the spirit of the definition of 'scientific inquiry' provided by the National Research Council:

> *"Scientific Inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world." (NRC, 1996, p. 23)*

These guidelines were developed based on key ideas from the National Research Council's *America's Lab Report* and *National Science Education Standards* and AAAS Project 2061's *Benchmarks for Scientific Literacy,* along with additional input from the research literature, new rubrics, and examples. These and other publications describe as best practice an inquiry approach to science instruction, with active student investigations at the heart of an integrated instructional progression. We support the NRC's statement that "Learning science is an active process. Learning science is something students do, not something that is done to them" (NRC, 1996, p. 20).

We first review the relevant research literature describing the current state of traditional classroom labs and new developments in remote, online, and simulated labs. The remainder of the publication is divided into three major sections:

A. **Guidelines for Student Scientific Investigations.** This section identifies 14 guidelines, adapted from *America's Lab Report* and *Benchmarks for Science Literacy,* which provide a framework for the overall scope, content, and processes of student scientific investigations. This framework is intended to inform, at a high level, the design of student scientific investigations (virtual or otherwise) including the range of technologies and approaches that can be utilized. Our intent is for these guidelines to be used to evaluate (and guide the development of) quality learning experiences in online courses, although they apply just as well to traditional classroom settings.

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[1] An online (or virtual) science course may include both online (computer-based) and physical (hands-on) activities. The term "online course" as used herein does not necessarily imply that all the activities or investigations that comprise that course are conducted purely online. Because we include the full range of student scientific investigations (computer-based and otherwise), the goals, guidelines, and standards described in this document are equally applicable to traditional classroom-based science instruction as well.

B. **Learning Goals for Student Scientific Investigations.** In *America's Lab Report,* the *National Research Council* identified 7 goals for scientific investigation. We accept this set of 7 goals as the desired target of a comprehensive science program. These goals define, in part, *what* should be taught. In this section we elaborate the meaning of each goal, provide examples whenever possible, and identify the research literature that informs those learning goals. We further explain why online courses are able meet all 7 standards and thus provide students with a complete science learning experience.

C. **Curriculum Design and Integration Standards.** The National Research Council further described four curriculum design traits instrumental in accomplishing the 7 learning goals. These "design standards" define *how* science courses should be structured. This section accepts those traits as standards for curriculum design for a science course that seeks to meet the 7 goals for scientific investigations. We discuss how virtual experiences are not just as effective, but possibly more effective, at reliably meeting these standards than traditional classroom-based laboratory experiences.

Background

The mission of the International Association for K-12 Online Learning (iNACOL) is to increase educational opportunities and enhance learning by providing collegial expertise and leadership in K-12 online teaching and learning. iNACOL members in the online learning community are committed to providing access to quality online science courses and teachers. The issues of access and quality are especially critical in the area of laboratory science courses. As the NRC points out in *America's Lab Report*, "most high school students participate in a limited range of laboratory activities that do not help them to fully understand science process" (NRC, 2006, p. 6). The NRC report concluded that "the quality of current laboratory experiences is poor for most students" (NRC, 2006, p. 6). Even more troubling, "students in schools with higher concentrations of non-Asian minorities spend less time in laboratory instruction than students in other schools, and students in lower level science classes spend less time in laboratory instruction than more advanced science classes. And some students have no access to any type of laboratory experience" (NRC, 2006, p. 6). Researchers have argued that the opportunities to do experiments and collect "real" data are often insufficient (del Alamo et al., 2003; Feisel and Rosa, 2005; Hofstein and Lunetta, 2004). Informed by these and the NRC findings, we do not seek to simply replicate the "classroom laboratory" experience in online courses; we seek instead to provide online learners with an investigative science learning experience that is improved over that of traditional laboratory science classrooms.

Scientific experimentation has powerful educational value by engaging students deeply in both the content and processes of science and by providing a practical perspective and cognitive connection to the theoretical materials presented in a classroom setting. Almost all educators agree that exposure to scientific investigations is an important part of learning science. We believe that online science courses, consisting of a thoughtfully designed sequence of investigations that are deeply interconnected with the relevant content instruction, can provide this exposure equally as well (and sometimes better) than traditional classroom-based experiences.

Scientific inquiry, both in traditional courses and online courses, can include a variety of learning experiences, including simulated, virtual, remote, and physical hands-on experimentation. The debate over the relative merits of simulated, virtual, remote, and hands-on labs has been going on for decades and is unresolved in the STEM education community (see Ma and Nickerson, 2006 for a review). Those who advocate the use of simulations cite the lack of resources, lab space, and teacher time to use real labs. Proponents of hands-on labs maintain that the pedagogy and experience with real labs and their unexpected outcomes can not be replaced with simulations (Albu et al., 2004, Srinivasan et al., 2006). The research literature comparing efficacy of remote, simulated, and hands-on labs has shown that in most cases there is no significant and consistent difference in learning outcomes between students doing hands-on vs. remote labs (Ma and Nickerson, 2006, Triona and Klahr, 2003). We believe the question should not be whether one approach is better than another, but rather how to combine the approaches in the most efficacious way for student learning and engagement in a particular scientific discipline whatever the student's physical surroundings.

Virtual laboratories have several important advantages that make them important parts of a total inquiry design. With no time required for setting up, breaking down, or clearing equipment, lab experiences can be integrated seamlessly into the instructional process without losing any time on "housekeeping" tasks. Virtual labs are also excellent replacements for the many lab activities that are no longer included in classroom high school instruction or are included only as demonstrations because of safety concerns. Virtual laboratories also allow access to processes, equipment, and materials that are not available in a typical high school due to cost, space, security, or other pragmatic constraints.

There is growing support for the idea of remote online labs (Ma & Nickerson, 2006). Online labs give students experience with real experiments and real data without as many restrictions on resources, lab space and access (Corter et al., 2004, Nedic, Machotka and Nafalski, 2003, Proske and Trodhandl, 2006). Professional scientific laboratory practices are increasingly computer-mediated (Barnard 1985; Oehmke and Wepfer 1985; Saltsburg et al. 1982; Tuma et al.1998). Unlike in school-based labs, it is increasingly rare to find a "pure" hands-on scientific laboratory. New combinations of various approaches to lab interactions are worth exploring. Online labs paired with the use of simulations can highlight the distinctions between models of physical processes or phenomena and their actual behavior captured and examined remotely (Sonnewald et al, 2003). A number of studies suggest that a combination of computer-mediated, hands-on, and simulated labs may be better than any single approach (Cohen and Scardamalia, 1998; Riffell and Sibley, 2004; Tuckman, 2002).

Another advantage of online labs is that they can provide students and teachers with more "time on task" to engage in important conceptual learning and less time spent on "housekeeping" tasks. The limited time available for most school-based labs, especially given NCLB-driven pressure to focus time on language arts and math instruction, prevents students from engaging in more value-added activities such as discussion, reflection, and other metacognitive tasks. If more time were available, traditional laboratory environments would be better able to support more meaningful learning processes (Champagne and Gunstone, 1990). Research has shown that integrating laboratory experiences with opportunities for wrestling with ideas and not just lab equipment results in better science learning (Gunstone and White, 1992). Online labs should also include prompts and supports for reflection and other metacognitive activities into the learning process (e.g., Loh et al, 2001).

Finally, lab experiences provide opportunities to teach collaboration, teamwork, and scientific discourse. While these goals can be met in face-to-face environments, they can also be achieved in computer-mediated environments. The current practice of science is changing rapidly with the advent of large-scale, distributed, multi-institution and multi-national scientific collaboratories. Preparing students to collaborate effectively as part of a distributed team, whether doing science or any other professional practice, should be an important component of any educational program. As Finholt and Olson (1997) observe, "laboratories as physical settings may have become less essential for scientific collaboration than was formerly the case" (p. 28).

The National Educational Technology Plan (2005) published by the U.S. Department of Education recommended that quality standards for online courses should mirror those of traditional courses. The documents and recommendations upon which the guidelines in this publication are based were designed exclusively for traditional courses. The quality criteria developed in this report demonstrate that online courses can meet or exceed all of the instructional goals of traditional courses, and these criteria can be used to evaluate student scientific investigations regardless of whether they take place in traditional classrooms or in online courses.

A. Guidelines for Student Scientific Investigations

DEFINITION OF STUDENT SCIENTIFIC INVESTIGATIONS

1. Scientists both within and across disciplines differ greatly in what phenomena they study and how they go about their work. Scientific investigations take different forms depending on what phenomena are being studied and what questions are being investigated. Student scientific investigations should, to the greatest extent possible, be authentic matches to the methods and approaches used by scientists in the discipline being studied.
2. Whenever practical, scientific investigations should provide opportunities for students to interact directly with the material world or with data drawn from the material world, using the tools, data collection techniques, models, and theories of science. Computer technologies may provide the best means for investigating phenomena when direct interactions are not practical (see Guidelines 4-9).
3. Scientific investigations should involve the collection of relevant data, the analysis of sources of error and noise, the use of logical reasoning, and the application of imagination in devising hypotheses and explanations to make sense of the collected data.

COMPUTER TECHNOLOGIES AND STUDENT SCIENTIFIC INVESTIGATIONS

4. Scientific investigations may consist of direct interaction with phenomena, interaction with phenomena mediated through computers or other instruments, the use of computer models, visualizations, or simulations, or interactions with large scientific databases, along with other investigative tools and techniques.
5. Interactive computer models, visualizations, and other representations (e.g., videos, images, and animations) can be useful in providing students with scaffolded representations of natural phenomena that are difficult to see and understand in the real world and in illustrating conceptual interrelationships and connections between multiple linked representations.
6. Computer simulations and other representations can be useful in allowing students to explore and observe phenomena that are too expensive, infeasible, or dangerous to interact with directly.
7. Providing students with access to large scientific databases using appropriately structured interfaces can support development of students' conceptual understanding and understanding of the data analysis process. Focusing students on causal explanation and argumentation based on the data analysis process can help them move from a descriptive, phenomenological view of science to one that considers theoretical issues of cause.
8. Computers and networks can provide students with remote access to scientific instruments that allows them to conduct scientific investigations that might otherwise be unavailable to them.
9. Interactions with computer-based representations and simulations of natural phenomena and large scientific databases should be integrated whenever possible into a thoughtful sequence of instruction that also includes direct interaction with the phenomena being studied.

DESIGN OF STUDENT SCIENTIFIC INVESTIGATIONS

10. Effective scientific investigations should have clear learning goals that guide the design of the experience.
11. Scientific investigations should be thoughtfully sequenced into the flow of science instruction and include ample opportunities for reflection and other metacognitive activities that support students in making sense of and understanding the purposes for the investigation.
12. Instructional units should integrate exploration of content with process through scientific investigations.
13. Scientific investigations and the surrounding instructional activities should support the development of important student scientific abilities including articulating hypotheses, constructing and evaluating scientific explanations, making sense of patterns in data, and identifying and controlling possible sources of experimental bias or error.
14. A student scientific investigation need not address all learning goals by itself; it may focus on an appropriate subset of learning goals. A science course consisting of a thoughtfully-designed sequence of scientific investigations and surrounding activities should seek to address the full set of learning goals.

B. Learning Goals for Student Scientific Investigations

Overview

Any analysis of a science course that includes labs and other forms of scientific investigation must begin by questioning why labs are included in a course to begin with. If we understand why these activities are included within a science course, we can then evaluate the degree to which a course achieves that purpose. As a part of its analysis of lab programs, The National Research Council (NRC) established seven goals for high school lab programs.

1. Enhancing mastery of subject matter
2. Developing scientific reasoning
3. Understanding the complexity and ambiguity of empirical work
4. Developing practical skills
5. Understanding the nature of science
6. Cultivating interest in science and interest in learning science
7. Developing teamwork skills

America's Lab Report found that the kinds of lab programs students usually encounter, which it calls "typical labs," do a poor job of meeting any of those goals. In contrast, they found that programs that followed its recommendations, which it called "integrated labs," were superior in reaching most of the goals and at least as good in reaching the rest.

Although it may seem to be a simple adjustment for high schools to adapt the recommended changes, *America's Lab Report* described factors that made such a change unlikely, not the least of which is that current teacher preparation programs do not teach it, and it is rarely included in continuing education for existing teachers (NRC, 2006, pp.7-8, pp. 138-167).

The following standards for student scientific investigations are therefore taken directly from the seven goals identified by the NRC in *America's Lab Report*. A carefully designed science instructional program can achieve all seven standards, whether the program is delivered in a classroom or online setting. It is not necessary for each investigation or activity to meet all seven goals, but the instructional program as a whole must meet these goals. In order to meet these goals/standards, a course must use instructional processes to ensure that these activities are properly integrated into instruction. Those processes are identified as standards in Section C.

1. Enhancing mastery of subject matter

As with all disciplines, the instructional goals for a science course include both established facts and concepts (content) and the skills used by professionals in that field (process). The National Research Council found that in typical programs, these are taught as if they were isolated and unrelated educational goals. This is not, however, the way modern educational theorists view them. Theories of student learning styles agree that kinesthetic activities and other active learning experience help students learn content (Newmann and Wehlage, 1993). For example, a student who performs a titration of hydrochloric acid and sodium hydroxide should better understand the concept of molarity than will a student who only receives classroom instruction in this concept.

The National Research Council, however, found no evidence that this was true for typical lab programs. In fact, a review of research indicated that students who participated in typical labs had no greater understanding of science concepts than did students who received classroom instruction only (NRC, 2006, pp. 88-89). Because of the research indicating that typical lab activities do not support content learning, some educators have even suggested limiting the amount of time students spend in lab activities so that they will have more time for classroom instruction in the subject matter (NRC, 2006, pp. 30-31).

The reason for this appears to be that typical lab experiences are too isolated from content instruction. In typical lab experiences, students perform a process without a clear understanding of the relation of that process to content. Students learn how to perform a titration, for example, without a clear understanding of why they are doing a titration or what the results mean in terms of scientific concepts. Another factor is that typical labs that attempt to demonstrate scientific concepts usually do so by having students follow set processes that confirm something that has already been taught, an approach that has limited instructional benefit.

In contrast, inquiry activities that are integrated with metacognitive learning experiences and that include the manipulation of ideas rather than materials and procedures have been shown in numerous studies to enhance student understanding of facts and concepts (NRC, 2006, p. 89). In contrast to labs designed to illustrate concepts already learned, an integrated program can use a constructivist approach (Teachnology, 2007) in which students make observations and draw conclusions about concepts prior to receiving explicit instruction. Studies have shown that students frequently have intuitive notions that are different from scientific conceptions, and these intuitive notions are resistive to change. The NRC found that "Emerging studies indicate that exposure to these integrated instructional units leads to demonstrable gains in student mastery of a number of science topics in comparison to more traditional approaches" (NRC, 2006, pp. 89-90).

The instructional design features consistent with improving student mastery of subject matter include the close integration of investigative activities into content, a merging of content instruction and process instruction, and reflection on the meaning of the learning activity once it is completed. Just as importantly, the instructional purpose of the lab must be communicated clearly to the student. These types of instructional activities are not only available in online courses they may in fact be able to perform them better than traditional courses. With no need to set up or break down lots of equipment either at all (for truly on-line experiences) or for a large group, inquiry activities can be integrated seamlessly into instruction, providing clear demonstrations of scientific principles at the most opportune moment to enhance student learning. In fact, in summarizing the types of activities that were most effective, the NRC noted that "Many, but not all, of these instructional units combine computer-based simulations of the phenomena under study with direct interactions with these phenomena" (NRC, 2006, p. 90).

Another advantage of online investigations relates to time. Since an online class is not usually constrained by a class period, and because there is no time spent setting up or breaking down equipment, the student is not limited by typical school time constraints. Investigation can take as long as is necessary, and it can be repeated if results are not clearly understood or if results do not clearly match expectations. The opportunity for repeated trials reduces the common student temptation to alter or "fudge" results to match their misconceptions. When a lab is repeated with the same results it helps students build the confidence to discard conceptions that are not scientifically sound and engage in the often difficult work of changing their conceptions. The student also has the time to confer with classmates about results and receive focused feedback from the teacher.

2. Developing scientific reasoning

The processes associated with scientific reasoning are important to science instruction. *America's Lab Report* notes in several places (pp 76-77, 90-92) that the general public has a poor understanding of what it means to think like a scientist. Students may be taught the various kinds of scientific processes and valid reasoning principles, but they need the opportunity to practice these reasoning skills as well. Instructional design that integrates inquiry activities into learning and that encourages students to participate in designing the process of investigation and drawing and supporting conclusions helps students practice scientific reasoning and develop these skills.

In a typical science course, classroom instruction focuses upon learning content, and laboratory experiences focus upon following specified procedures. Students spend little or no time planning investigations or interpreting results. Consequently, a student in a typical science program will not have much if any experience developing scientific reasoning skills. An integrated laboratory program in a course that is inquiry-based will instead promote a variety of skills associated with scientific reasoning. According to the NRC, these include the ability to

- identify questions and concepts that guide scientific investigations;
- design and conduct scientific investigations;
- develop and revise scientific explanations and models;
- recognize and analyze alternative explanations and models; and
- make and defend a scientific argument, including writing, reviewing information, using scientific language appropriately, constructing a reasoned argument, and responding to critical comments. (NRC, 2006, pp. 76-77)

An integrated learning approach blends scientific investigation with small group discussion, and other forms of science instruction. Studies indicate that careful instructional scaffolding is necessary to support the development of scientific reasoning. With such an approach, students can be taught to

- design experiments (Schauble et al., 1995; White and Frederiksen, 1998, in NRC, 2006, p. 91),
- make predictions (Friedler, Nachmias, and Linn, 1990, in NRC, 2006, p. 91),
- interpret and explain data (Bell and Linn, 2000; Coleman, 1998; Hatano and Inagaki, 1991; Meyer and Woodruff, 1997; Millar, 1998; Rosebery, Warren, and Conant, 1992; Sandoval and Millwood, 2005, in NRC, 2006, p. 91),
- recognize discrepancies between predicted and observed outcomes (Friedler et al., 1990, in NRC, 2006, p. 91) and
- design good experiments (Dunbar, 1993; Kuhn et al., 1992; Schauble et al., 1995; Schauble, Klopfer, and Raghavan, 1991, in NRC, 2006, p. 91, Chen and Klahr 1999, Li and Klahr 2006, Li, Klahr, and Jabbour 2006).

The ability to construct scientific arguments is now considered a core scientific process, and a well-designed science course should include such instruction. In effective instructional practice, students must learn to "coordinate theoretical claims with evidence taken from their laboratory investigations" (NRC, 2006, p. 92).

3. Understanding the complexity and ambiguity of empirical work

One aspect of the nature of science that requires special attention is the complexity and ambiguity of empirical work. Similar or even identical experiments performed at different times or by different people can yield different results. Some experimental results can seem to contradict accepted scientific principles. A comparison of research studies, such as those examined for this and other such reports, can include contradictory conclusions. Students who have been led to see science as a collection of facts or clearly defined lab procedures with results that firmly support received instruction are confused when they experience this. Students must be able to expect such outcomes and know how to deal with them; including troubleshooting equipment; rechecking data observations and analysis; examining the parameters, assumptions, and study definitions in contradictory studies; and generally performing the kind of follow-up investigations done within the scientific community.

According to the National Research Council, "Interacting with the unconstrained environment of the material world in scientific investigations may help students concretely understand the inherent complexity and ambiguity of natural phenomena" (NRC, 2006, p. 97). One of the problems addressed in *America's Lab Report* is a typical misunderstanding among the general population about the nature of empirical studies. The population in general expects experimentation to create clear and unambiguous results, which is seldom the case in real world science. Properly designed scientific investigations will allow students to observe the complexities and ambiguities inherent in true investigations, and students should be involved in activities like "troubleshooting equipment used to make observations, understanding measurement error, and interpreting and aggregating the resulting data" (p. 77).

In typical science courses, instructors work hard to remove these complexities and ambiguities. When students make observations or gather data that seem to contradict what was expected or the principles that were taught in their instruction, the resulting confusion causes uncomfortable moments in the classroom (Olsen, Hewson, and Lyons, 1996; Hammer, 1997, cited in NRC, 2006, p. 118). Lab manuals and teacher-directed procedures are therefore often designed to minimize or eliminate such confusion (Olsen, et al., 1996, cited in NRC, 2006, p. 118). Consequently, students in typical courses receive an inaccurate perception of the nature of empirical study. A study by Glagovich and Swierczynski (2004; cited in NRC, 2006, p. 148) similarly demonstrated the challenges students face when they encounter procedures that don't work, indicating that their previous laboratory experiences had not properly prepared them for such occasions.

A well-designed scientific investigation program, in contrast, will include opportunities for students to experience this effectively without it leading to confusion. Another of the seven goals, developing teamwork skills, can help with this process. Students working in a team can perform activities independently, compare results, and then discuss and account for discrepancies. Rather than see experimental errors as hindrances to learning, an instructional designer will see them as opportunities for greater learning and include the expectation of experimental errors into the course design rather than carefully screen them out.

Online education courses have several advantages over traditional courses in meeting this standard. Students can be placed in teams in which each student performs the activity separately, and they can work collaboratively to discuss differing results. Experiments can be repeated to verify or check results. Traditional classes are limited in their ability to provide more than one investigative activity, whether the work is done individually or in teams.

4. Developing practical skills

During laboratory experience, students learn to use the tools and the conventions of science. This includes the use of scientific equipment and the conventions of science, including measuring, observing, and following procedures. Many instructors have limited their understanding of this goal to the handling and manipulation of lab equipment, such as wearing goggles for safety, using tongs to grasp hot objects, handling a scalpel, using balance beams properly, and adjusting Bunsen burner flames. While these skills are valuable, they are easily learned and are not the primary purpose of this goal. More important are the effective application of the appropriate scientific process to a new investigation, making accurate observations, and generally following accepted procedures to ensure valid results.

This has long been held to be an important goal for laboratory experiences, but the National Research Council was able to find little research that measured the development of these skills or their importance in the educational process. Some studies have indicated that students need training in taking measurements to improve the efficiency and the effectiveness of later experimentation, indicating a need for "prelab" instruction or lab-like activities designed to teach procedures so that students can apply them in later activities.

America's Lab Report indicates little advantage of one mode of laboratory instruction over another regarding this goal. It does indicate, however, that an inquiry-based, integrated instructional approach will promote the importance of skills related to learning "scientific ideas with real understanding and on developing their skills at investigating scientific phenomena, rather than on particular laboratory techniques, such as taking accurate measurements or manipulating equipment" (NRC,2006, p. 93). Students can learn to manipulate lab equipment in almost any kind of lab activity, but the truly important activities related to understanding (and not just following) procedures requires an integrated approach.

Consideration must be given to the primary purposes of high school science instruction. The NRC report refers to college courses in which "a primary goal of a program or course is to train students for jobs in laboratory settings" (NRC, 2006, p. 92). This is not, however, a primary goal of high school instruction, and students who seek such jobs will have completed a full college program before they enter the workforce. The small percentage of high school science students who will some day work in a lab setting will have had extensive training in laboratory skills after completing high school.

Students engaged in traditional labs will have greater experience using the laboratory equipment than students involved in mostly online activities. However, many of the tools and equipment used in high school laboratories are no longer the tools and equipment used in colleges and professional laboratories. High school students who become adept at adjusting the flame of a Bunsen burner will find little practical benefit for that skill after graduation. In fact, modern laboratory equipment at higher education and professional levels integrates computers for observation and measurement to the degree that the online student may have an advantage in gaining practical skills (Ma and Nickerson, 2006, p. 10). In addition, many instructional activities, such as flight training and even medical school anatomy studies engage the student extensively in computer simulations before practicing on real airplanes or dissections.

In a review of studies related to laboratory simulations and remote labs, Ma and Nickerson (2006, pp-10-12) describe research indicating that a psychological sense of presence is as effective for students as physical presence. Students using simulations and remote labs performed as well on subsequent assessments as students using physical labs. Ma and Nickerson cite Biocca (2001) and Bentley et al (2003), who agree that the perception of being present was as effective as actually being present.

5. Understanding of the nature of science

As has been cited in the goals related to scientific reasoning and the complexities and ambiguities of empirical work, *America's Lab Report* cites a historic lack of understanding of the nature of science on the part of students. Students see science as a collection of laws and facts without any real understanding of how existing concepts came into being, how these existing ideas are reshaped with new discoveries, how an accepted theory differs from wild guesses at one extreme to firm facts on the other, and how new concepts and theories emerge through investigations. Students do not generally understand that "science is a human endeavor that seeks to understand the material world and that scientific theories, models, and explanations change over time on the basis of new evidence" (NRC, 2006, p. 77). Few students develop "a notion of science as model building and experimentation, in an ongoing process of testing and revision" (NRC, p. 94). A course that focuses instruction on learning facts and concepts encourages this misunderstanding. Although many assume that laboratory experiences provide such an understanding, but nearly all research indicates otherwise. Laboratory procedures that follow carefully predetermined procedures do little to help.

Understanding the nature of science requires a carefully integrated curriculum that explicitly teaches these concepts in the instructional phase and reinforces this understanding through an investigative process. This reinforcement can occur through a variety of instructional strategies, including constructivist activities and activities that allow students to apply scientific processes to create their own scientific investigations to solve problems. Such experiences include metacognitive assignments that allow students to reflect on their learning and how their experiences relate to scientific principles and procedures.

Research indicates, however, that laboratory experiences by themselves will not provide this understanding. *America's Lab Report* provides examples of effective lessons. This includes an online site with instructional software (http://thinkertools.org/) as an example of instructional practices that support understanding of the nature of science. Research by White and Frederiksen (1998) supported the idea that such an integrated approach helped students "acquire knowledge of the forms that scientific laws, models, and theories can take, and of how the development of scientific theories is related to empirical evidence" (p. 72). Both traditional classes and online classes have the ability to integrate these learning skills to meet this goal.

On the other hand, according to the NRC, no laboratory program can reach this goal without the accompanying integrated instructional activities (NRC, 2006, pp. 93-95). This is indicative of the importance of fully integrating instruction and investigative processes in instructional design.

6. Cultivating interest in science and interest in learning science

Effective instruction in any academic discipline cultivates an interest in the subject and motivates students to continue learning more about the subject. Ever since Fred M. Newmann and Gary G. Wehlage described five principles of authentic instruction (1993), educators have advocated authentic instruction as an effective instructional practice, one that has a particular advantage because it builds student interest and motivation. Even though science course have featured labs to varying degrees for more than 150 years, scientific investigations, labs, and any other activity in which students do the kind of work or activities that scientists do are applications of the five principles of authentic instruction in the discipline of science.

The five principles of authentic instruction are consistent with the integrated approach to science investigations:

1. Higher order thinking skills
2. Depth of knowledge
3. Connectedness to the world beyond the classroom
4. Substantive conversation
5. Social support for student achievement

Similarly, the National Research Council believes that "as a result of scientific investigations that make science 'come alive,' students may become interested in learning more about science and see it as relevant to everyday life" (p. 77). Research on the ability of typical lab programs to cultivate such an interest is not extensive, and it is difficult to distinguish between studies gauging interest in science and studies gauging interest in the labs themselves. The results of those studies are mixed. Many studies of typical labs show negative consequences when the labs are disconnected from classroom activities and students are unclear about the purposes and procedures (Schauble et al., 1995; Champagne et al., 1985; Eylon and Linn, 1988; Tasker, 1981; White, 1998).

Although research on the benefits of integrated lab experiences is also sparse, the evidence that does exist suggests a positive correlation between an integrated lab program and student interest. Studies of the ThinkerTools program (http://thinkertools.org/) suggest that this integrated, computer-based program has a positive benefit on student attitudes toward science (White

and Frederiksen, 1998). An extensive study involving multiple countries (including the United States) indicated that positive student attitudes toward science are strongly associated with cohesiveness (the extent to which students know, help, and are supportive of one another) and integration (the extent to which laboratory activities are integrated with non-laboratory and theory classes) (Fraser et al.,1995; Wong and Fraser, 1995; in NRC p. 97).

7. Development of teamwork skills

According to NRC, scientific investigations "promote a student's ability to collaborate effectively with others in carrying out complex tasks, to share the work of the task, to assume different roles at different times, and to contribute and respond to ideas" (p. 77). Teamwork and collaboration are now commonplace in the scientific community, and the image of the lone scientist working in isolation is now mostly a relic of the past. Students need to learn effective collaborative processes if they are to be effective members of that community.

Although part of the reason for this goal is the collaboration within the scientific community, the primary impetus for the inclusion of this goal comes from the science of instructional design. Research in effective instructional strategies indicates that well-designed collaborative authentic instruction can be among the most effective possible strategies to enhance student learning. Unfortunately, poorly designed collaborative processes can undermine instruction and student achievement. Teamwork skills must be taught as a part of the instructional process if they are to be used effectively. Some teachers even introduce investigate processes early in the course for the primary purpose of teaching effective teamwork skills (Danielson, C. 2002; Marzano, Pickering, and Pollock, 2001; Marzano, 2007; Marzano, 2003).

Teamwork is also included as one of the five standards of authentic instruction (Newmann and Wehlage, 1993, 8-12). The fourth standard, substantive conversation requires interaction marked by these characteristics:

High levels of substantive conversation are indicated by three features:

1. There is considerable interaction about the ideas of a topic (the talk is about disciplined subject matter and includes indicators of higher-order thinking such as making distinctions, applying ideas, forming generalizations, raising questions, and not just reporting experiences, facts, definitions, or procedures).
2. Sharing of ideas is evident in exchanges that are not completely scripted or controlled (as in a teacher-led recitation). Sharing is best illustrated when participants explain themselves or ask questions in complete sentences and when they respond directly to comments of previous speakers.
3. The dialogue builds coherently on participants' ideas to promote improved collective understanding of a theme or topic.

In typical laboratory experiences, teamwork is usually limited to the concept of lab partners, which often means nothing more than students taking turns performing the lab procedures while the partner watches. The primary instructional purpose is to divide limited lab equipment and space among a large number of students. Some studies indicate that when lab partners are of mixed genders, girls end up doing most of the watching, while the boys do most of the handling of equipment (Jovanovic and King, 1998; in NRC, p. 93).

True collaborative work in a scientific investigation is much more complex, with students sharing ideas about hypotheses, procedures, and conclusions. If course instruction is designed in this way, scientific investigations that use online lab programs can provide an advantage over traditional labs, since all students can do their work independently, share results and observations, and come to collaborative conclusions. Scientific investigations that include literature and database research can also benefit from collaborative processes, as teams of students can divide research duties and share results, thus allowing a team to complete a much more comprehensive search in much less time.

C. Curriculum Design and Integration Standards

If a science course is to meet the goals/standards listed Section B, it must use effective instructional strategies. The standards described for the design of curriculum and the integration of scientific inquiry activities with instruction are consistent with current thinking on best practices in instruction for all curriculum subjects. The National Research Council has published several reports identifying how students learn (NRC, 1999, 2005; Glaser 1994), and educational theorists around the world have been calling for instructional practices that include active learning, higher-order thinking, performance assessment, and authentic learning for many years. The scientific inquiry activities and lab procedures advocated by this report are nothing more than applications of these principles to science instruction.

The following four curriculum standards were identified as principles of effective laboratory experiences by the National Research Council in *America's Lab Report* (NRC, 2006, pp.101-102):

1. Clearly Communicated Purposes
2. Sequenced into the Flow of Instruction
3. Integrated Learning of Science Concepts and Processes
4. Ongoing Discussion and Reflection

Unfortunately, The National Research Council found that in science instruction, as with other disciplines, these theories too often are not manifested in actual classroom instruction. For example, one NRC study found that chemistry laboratory experiences tended to be verifications of chemistry concepts rather than problem-solving experiences (NRC, 2002, p. 356, in NRC 2006 p. 79). That same study found that Biology AP courses tend to use "cookbook" labs (NRC, 2002, p. 292, in NRC 2006 p. 79). A 2004 study by Hofstein and Lunetta found that lab activities are low-level and routine activities (p. 39). Studies of the effectiveness of NSF-created curricula and the best-designed AP activities were frequently not carried out as intended when actually taught in the classroom (NRC, 2006, pp. 123-126). As a part of its preparation for *America's Lab Report*, the National Research Council examined the initial teacher preparation and subsequent staff development opportunities for teachers and found that science teachers were generally given no true instruction in these methodologies in either case (NRC, 2006, pp. 138-151).

Although traditional classes could be designed with National Research Council guidelines in mind, *America's Lab Report* holds little hope for that in light of the identified lack of training for teachers and curriculum developers. Consequently, online courses that have been carefully designed in alignment with accepted standards of instruction have an advantage over traditional classes.

Because such lessons must be almost completely prepared in advance, online teachers rarely deviate from the original course design. Thus, an online course carefully designed by a curriculum expert to align with curriculum standards will be followed as intended, regardless of which individual teacher is assigned to the class. And, since the courses are designed to be accomplished regardless of the student's physical surroundings, the instructional design is more likely to actually be accomplished because it does not rely on time-limited exposure to a specific set-up of physical equipment.

1. Clearly Communicated Purposes

The National Research Council believes that "Effective laboratory experiences have clear learning goals that guide the design of the experience" (NRC, 2006, p. 101). Students learn little when the goals of a laboratory experience are not clear to them, but when the teacher clearly communicates the purpose of the activity, students are able to carry it out successfully and achieve the desired purpose.

The purposes of a laboratory activity are related to scientific concepts, not following specific laboratory procedures. Research indicates, however, that typical school labs tend to focus so intently upon following procedures that the true purpose of the activity is forgotten. This leads to "cookbook" activities that are not related to the purposes of science instruction (Tobin and Gallagher 1987; De Carlo and Rubba, 1994; Priestley, Priestley, and Schmuckler, 1997; Millar, 2004; Olsen et al., 1996, p. 785, in NRC, 2006, 121-124). In contrast, studies of integrated science units with clearly defined purposes show significant improvement in student learning (Linn, 1997; Linn and Songer, 1991; Linn and Hsi, 2000, in NRC, 2006, p. 85).

An inquiry activity that meets this standard will be designed to ensure that students learn specific concepts. Those concepts will be clearly communicated to students throughout the process, and students will be assessed on their ability to achieve the instructional purpose of the activity.

2. Sequenced into the Flow of Instruction

According to *America's Lab Report*, "Effective laboratory experiences are thoughtfully sequenced into the flow of classroom science instruction. That is, they are explicitly linked to what has come before and what will come after" (NRC, 2006, p. 102). Perhaps the most significant finding of this study was the degree to which laboratory activities are isolated in classroom instruction (Sutman, Schmuckler, Hilosky, Priestley, and Priestley, 1996; Linn, Songer, and Eylon, 1996; Linn, 2003; in NRC, 2006, p. 124)). In contrast, a high quality instructional program carefully integrates scientific investigations into a well-designed sequence of instruction, with these investigations serving an instructional purpose consistent with the objectives of the learning unit (see Linn, Davis,and Bell, 2004a; Cobb et al., 2003; Design-Based Research Collective, 2003; in NRC, 2006, p. 81.) Such lessons weave a wide variety of inquiry activities with other instructional activities. The National Research Council found that

Nascent research on integrated instructional units suggests that both framing a particular laboratory experience ahead of time and following it with activities that help students make sense of the experience are crucial in using a laboratory experience to support science learning. This "integration" approach draws on earlier research showing that intervention and negotiation with an authority, usually a teacher, was essential to help students make meaning out of their laboratory activities (Driver, 1995). (NRC, 2006, p. 82)

Online learning programs are sometimes prevented from meeting this standard because they are often required to do separate lab activities from instruction by outside agencies. For example, the University of California a-g requirements for courses acceptable for college admission says "Online courses may be approved for credit toward the "d" requirement if they meet all the guidelines outlined above, including a supervised hands-on laboratory component comprising at least 20% of the course (e.g., UCCP courses)" (University of California, 2007). This means that students who are taking online courses must contract with an institution that can provide the laboratory experiences for the student, which essentially forces a separation of the laboratory experiences from instruction. Such requirements actually force online programs to use less optimal instructional technique and lower the educational quality of the classes in order to meet a requirement for hands-on labs.

Virtual classes can integrate scientific investigations into the sequence of instruction more easily than traditional classes if they are allowed instead to use a full range of possible inquiry activities, including those described by organizations like AAAS and listed in *America's Lab Report* (NRC, 2006, pp. 31-32). In part by using computer based instruction, with less required time to set up, break down, and clean for large, scheduled, groups, inquiry activities can be fully integrated into instruction, optimizing learning from these experiences.

3. Integrated Learning of Science Concepts and Processes

In previous studies, the National Research Council (National Research Council, 1999, 2001) found that conceptual understanding, scientific reasoning, and practical skills need to be bended in the instructional process if the class is going to be effective in achieving educational goals. Typical science classes see content and process as two different instructional goals. Classroom activities focus on the acquisition of science facts and concepts. Laboratory experiences are viewed as the opportunity to learn process skills (NRC, 2006, 133).

The complete integration of process and content is viewed today as a critical component of effective instruction in all disciplines. Students in well-designed history classes learn to form hypotheses about historical events and movements and draw conclusions from data and document review rather than merely memorize the dates and events. State content standards in literature do not require demonstration of knowledge about specific authors and texts. Students are instead expected to be able to acquire the skills needed to read and draw conclusions related to an author's literary purpose. Educators have learned that when content and process are merged, student interest, skill acquisition, reasoning ability, and content knowledge all improve.

As described earlier, requirements that online education courses separate instruction and investigation by limiting investigations to isolated lab sessions nearly precludes the possibility of integrating content and process in instruction. Effective online classes can improve on traditional instruction by having students move back and forth continuously between lab activities and instructional activities. A single lab can be divided into multiple parts, with instructional activities, formative assessments, and practice activities blended into the process in a way that would be impossible to create in a traditional classroom or in an online class that requires that students go to a separate location for any investigative activities.

4. Ongoing Discussion and Reflection

The National Research Council believes that "Laboratory experiences are more likely to be effective when they focus students more on discussing the activities they have done during their laboratory experiences and reflecting on the meaning they can make from them, than on the laboratory activities themselves" (NRC, 2006, p. 102). Students need to have the time and opportunity to form hypotheses before experimentation and reflect on their ideas after experimentation. Activities of this kind have been shown through ample research to help students achieve the goals identified for laboratory experiences, including the goals of mastery of subject matter, developing scientific reasoning, increasing interest in science and science learning, and developing teamwork skills.

Modern educators speak of developing a knowledge-centered environment. That encourages "students to reflect on their own learning progress (metacognition)." Research in cognition indicates that "learning is facilitated when individuals identify, monitor, and regulate their own thinking and learning." Effective problem solvers and learners can "determine what they already know and what else they need to know in any given situation, including when things are not going as expected" (NRC, 2006, p. 80). Gobert and Clement (1999) found that students with well developed metacognitive strategies have the ability to change their approach with when they are not working effectively, but students with less developed metacognitive skills continue to use the same strategies even after they have been proven to be ineffective.

Learning is also improved when it is taught in multiple contexts. When students encounter the same learning in a variety of instructional contexts, including direct instruction, laboratory activities, and discussions, they are more apt to come to a deeper and more complete understanding of it (Bransford and Schwartz, 2001; in NRC, 2006, pp. 80-81). *America's lab Report* argues that having only one context for content acquisition (the teacher or the text) works against the goal of understanding the nature of science, for the students tend to see science as a as immutable facts dispensed to a passive audience by an authority who knows all (Lemke, 1990, in NRC, 2006, pp. 80-81).

The National Research Council found ample research to indicate that in typical high school science programs, reflection and discussion are rare events. Typical students rarely have opportunities to share ideas in a community of learners. (Weiss, Banilower, McMahon, and Smith, 2001; DeCarlo and Rubba, 1994; Lunetta, 1998). Discussions that take place during laboratory experiences are almost always related to procedures (Hegarty-Hazel, 1990, cited in Lazarowitz and Tamir, 1994). When these discussions do occur, they are even more rarely done in small groups, meaning that in a typical discussion, only a small percentage of a class will have the opportunity to participate (NRC, 2006, p. 127).

Because a high quality online class has its instructional activities designed in advance, a well-designed curriculum will build in opportunities for ongoing discussion and reflection. An online Learning Management System can be set up to include large group threaded discussions, small group threaded discussions, and synchronous discussions using Voice Over Internet Protocol to allow verbal exchanges in real time. Unlike a typical traditional class, a large group threaded discussion can require 100% class participation. Unlike a typical traditional class, a teacher can choose to monitor all small group discussions, whether threaded or synchronous, because a permanent record is maintained of all such meetings. Students who are ill and unable to participate in any such activity are still able to review the recordings of the discussions that were missed.

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Appendix A

Integrated Lab Program Samples

Any attempt to examine samples of integrated investigation programs must be viewed with caution. As *America's Lab Report* notes, truly integrated programs in traditional schools are very rare, so few such programs exist there. Most early online education programs strove to imitate the typical school model, so most of those will have the same failings. Although individual instructional tasks that meet these high standards have been created and published over the last decade, most full course programs are only now fully integrating these approaches into instructional design. In reviewing the examples that follow, it is important to keep several key qualifiers in mind.

The ability of a course to meet these standards lies in the program as a whole, not in any individual component. Not every scientific investigation need meet every standard by itself. In fact, it is possible that an activity may have a very specific targeted instructional goal that is vital to the program but which may meet only a few of the goals of the program as a whole. For example, instructors who have successfully included teamwork processes in instruction, particularly in online instruction, have learned that students need to be taught teamwork processes and skills in order to be successful. A program may choose to include an investigative activity early in a course for the primary purpose of teaching teamwork skills, intentionally omitting other aspects of scientific investigation in order to ensure that students learn that important skill so they can apply it in later investigations. An individual sample of an investigation only shows a part of a more important and more complete whole and should not necessarily be expected to be representative of that whole.

Specific aspects of some investigations may make the application of some of the standards to that application challenging. In a traditional chemistry class, for example, many lab activities are conducted as teacher demonstrations because of the inherent dangers in those particular procedures. Some investigations may have limitations of other kinds that prevent the application of a specific standard to that activity. When that happens in a course, the course designer must ensure that other investigations help make a complete and comprehensive program.

The inherent danger of looking at even excellent samples is that reviewers may assume that the few samples they see are the only ways a course can meet the goals of scientific investigation. These standards can be met, however, by a great variety of instructional approaches and activities. New technological advances will bring new approaches to learning. No set of examples can encompass all possibilities, and a reviewer must keep in mind the ultimate goals of science instruction when examining the full scope of a program of scientific investigation.

Appendix B

Resources Cited by the National Resource Council in Support of all Goals (These references are not cited in this report; however, they are included here as helpful pointers to additional research related to science teaching and learning.)

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