What Do We Know about What Works?
Review of US Foundations' Programs in Secondary Chemistry Education

A Report to the Camille & Henry Dreyfus Foundation

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Executive Summary

The Camille and Henry Dreyfus Foundation is interested in identifying and addressing needs and opportunities in the chemical sciences, including chemistry education for children and adults. In this report, we discuss the results of a review conducted for the Foundation to examine "what works" in secondary chemistry education, as guidance for philanthropic efforts in this area. We have taken several approaches to answering this question:

- Profiling current giving to chemistry education in particular, and science education more generally, by private foundations;
- Examining what these foundations know about the outcomes of their efforts;
- Outlining evaluation approaches used by other foundations to gather data on the outcomes of their projects, that may serve as models for gathering better evidence about "what works";
- Reviewing the educational research literature to summarize research-based 'best practices' that might be used to shape foundation programs and to guide proposers.

Overview of the Report

First, we conducted an empirical study of foundations' giving practices in science education. We reviewed foundation web pages and philanthropic databases to compile a sample of foundations active in this arena, then investigated their activities through a mail survey and telephone interviews, augmented by annual reports and other public documents. We report on the findings of this study in Section 2 of the full report, presenting the findings in two forms:

- A profile of the current "landscape" of private foundation funding for science education. For this portion of the study, we selected 37 foundations that are key players in science education nationally or (in a few cases) regionally. In this analysis, we classify and describe the types of educational activities that each foundation supports to provide an overview of foundation activity in this area and the strategies they have selected.
- An analysis of "best practices" for secondary chemistry education, based on survey and/or telephone interview data from representatives of 16 foundations within the larger group above. In this qualitative analysis, we analyze foundation officers' collective advice on: the arenas where their foundations have chosen to work, and why; the critical elements for strong program design in these educational arenas; and the challenging issues of dissemination and sustainability of effective educational practice.

In addition, we analyzed these foundations' evaluation efforts to gather evidence of their own about "what works" in science education. While many foundations had not gathered extensive evidence, a few had tackled this problem in a serious manner. The evaluation approaches of four foundations chosen as case exemplars are discussed in Section 3.

In Section 4, we review the educational research literature pertinent to the study question. This review begins with a discussion of concerns about secondary chemistry education. It summarizes current understanding of how people learn and the implications of this understanding for practices and materials for classroom teaching and learning. Teacher professional development is addressed as a separate topic. When topics are addressed from the standpoint of the general science education research base, illustrations are provided that are specific to chemistry. In addition, some specific challenges of learning chemistry, and the

important role of laboratory work, are separately addressed.

Key Findings

- Of the 37 foundations in our sample, over half were active in three areas of science education, supporting informal (out-of-school) science education, teacher professional development, and student scholarships or internships.
- Other areas involving at least one-fourth of the foundations sampled include giving targeted to: classroom equipment or facilities; technology resources such as web sites; development of instructional materials; school-wide initiatives; support for employee donations and volunteerism; and special projects.
- Patterns of giving differed depending on the nature and goals of the foundation. In particular, corporate foundations tended to support different types of giving than other types.
- Many foundation representatives had limited information about "what works." Typically, they had information about the populations served and the activities conducted, but did not have evidence of the impact of project activities on those populations (e.g., changes in student interest or achievement). Few foundations required evaluation from their grantees, and thus had little data of more rigorous forms, for example comparing outcomes for program participants with non-participants or addressing why certain outcomes occurred (e.g., what about the program served to increase student interest?). Thus, their overall understanding of "what works" was limited to what could be gathered from site visits and from grantees' annual reports, which were reported to vary in depth and quality.
- Several foundation representatives reported making use of the educational research literature to identify needs and select strategies for improving science education. Their reports of "best practices" that they chose to support are well-aligned with the practices supported by the educational research literature. These best practices include:
    - The use of hands-on, minds-on, inquiry-based teaching and learning strategies;
    - The use of national and state standards to guide priorities for development of age-appropriate instructional materials that focus on important ideas in science;
    - The need for teachers to be both knowledgeable about content and well-versed in how to use effective teaching and learning strategies specific to the content they teach;
    - The importance of involving a range of stakeholders in projects from the beginning;
    - The need to take into account the school, district and state systems in which teachers work, and to align teacher professional development efforts with the requirements and initiatives of these systems;
    - The importance of explicitly addressing dissemination and sustainability of good work.
- Foundations' evaluation practices reflect a changing environment for evaluation and a growing interest in gathering evidence for the impact of charitable giving, beyond simply documenting the numbers and types of audiences reached.
- Foundations at the forefront of this shift were undertaking a range of strategies, including capacity development for their awardees, database development to standardize certain evaluation outcomes, meta-evaluation of individual project outcomes to derive a sense of

overall program outcomes, and use of internal and external evaluators to both counsel awardees about evaluation and to review outcomes across projects.

- It is apparent from our data that foundations that have articulated a "theory of change"—that is, a clear rationale for their choice of a certain area for giving and for why supporting this area will have an impact—are often the same as those that have undertaken evaluation efforts. By gathering evidence to use in refining and improving their theory of change and the specific choices for action that might best put their theories to work, these foundations view evaluating the impact of their work as part of the cycle that establishes directions for grant-making and improves outcomes. As one program officer put it, "We make strategic changes based on the evaluation data that we get back."
- It is beyond the scope of our task to advise the Foundation on its rationale for choosing a particular area of chemistry education in which to focus its efforts. However, in each area of chemistry educational research literature that we have reviewed, we have suggested some areas of need, and some key propositions that may be useful to the Foundation in articulating its choices clearly, guiding future proposers, reviewing and/or evaluating proposals.
  - Principles of "how people learn" from cognitive science research can be applied to classroom practice, instructional materials, and teacher professional development.
  - A number of existing, research-grounded curricula for elementary and middle school contain substantial chemistry content taught with inquiry-based teaching and learning methods. Needs lie in supporting schools to adopt and implement these curricula, preparing teachers to teach them well, and sustaining their use.
  - Several research-grounded curricula for introductory high school chemistry are available or under development. Needs lie in adoption and implementation, teacher support, and encouragement of inquiry approaches at the high school level. There appears to be a dearth of inquiry-based curricula for advanced high school chemistry.
  - Chemistry education research identifies several features that make chemistry challenging to learn. Needs exist for further research and for better application of research to practice in addressing chemical misconceptions and teaching chemical concepts effectively.
  - Laboratory work is an important aspect of chemistry learning, although the research base establishing what factors make lab work effective is less well-developed than in some other areas. Several current trends are reducing students' opportunities for lab work.
  - Research on teacher professional development identifies factors that make it effective, including coupling of content and pedagogy to develop teachers' pedagogical content knowledge; engagement of sufficient duration, with follow-up; and linkage to the systems in which teachers work.

1 Introduction: Context and Goals of the Study

The Camille and Henry Dreyfus Foundation, Inc., was established in 1946 by chemist, inventor and businessman Camille Dreyfus as a memorial to his brother Henry, also a chemist and his business partner. The purpose of the Foundation is "to advance the science of chemistry, chemical engineering and related sciences as a means of improving human relations and circumstances around the world." The Foundation is interested in identifying and addressing needs and opportunities in the chemical sciences, including chemistry education for children and adults. In this report, we discuss the results of a review conducted for the Foundation to examine "what works" in secondary chemistry education, as guidance for the Foundation's philanthropic efforts in this area.

1.1 Historical Overview

A brief historical overview provides some context for the Foundation's past work and experience in chemistry education. The Foundation's chemistry education activities have largely occurred through its Special Grants program. The earliest grants in education were made in 1991. In the 1990s, 28 special grants totaling over $730,000 were awarded to projects that targeted a variety of audiences. In the seven years from 2000 to 2006, both the size and the number of education grants increased: by the end of 2006, over $2.1 million had been awarded to 54 recipients proposing chemistry education activities (including this project).

Across both decades, the most common types of projects included outreach by university students and faculty to middle and high school students in or out of school; equipment to enhance laboratory work and technology access for schools; and workshops and research opportunities for teachers. Some projects addressed special groups of students, such as girls, minority students at urban schools, or rural schools. Some projects involved partnerships with particular schools or districts, while others offered resources or programs broadly to students in their region. A smaller number of projects addressed college education, targeting recruitment and preparation of students for college chemistry majors and/or teacher preparation. A few also addressed outreach to the general public through media efforts or museum exhibits; and research on chemical education (including this project). The majority of awardees were university chemistry faculty proposing to interact with K-12 schools or informal science institutions; a few projects came from the schools or informal organizations themselves. Thus the Foundation has a track record of interest and support for chemistry education across a broad span of types of educational activity.

1.2 Study Goals and Approaches

This study was requested by the Camille and Henry Dreyfus Foundation to inform its chemistry education giving. The study sought to discover "what works" in K-12 chemistry education, and thus to assist the Foundation in determining how its resources can best be targeted to make a difference.

The driving question for this study was "What do we know about what works in secondary chemistry education?" As it turned out, this question was not simple to answer. We took several approaches to answering this question, including:

- Profiling current efforts funded by private foundations;
- Examining what is known about the outcomes of these efforts;

- Outlining evaluation approaches used by other foundations to gather data on the outcomes of their projects, and which may serve as models for the Dreyfus Foundation;
- Reviewing the education literature to summarize research-based 'best practices' that might be used to shape foundation programs and guide proposers.

Below, we summarize these approaches and outline the findings from each approach that are reported in the following sections.

1) What do we know about "what works" in secondary chemistry education?

Originally we conceived, in conversation with Dr. Mark Cardillo from the Camille and Henry Dreyfus Foundation, an empirical approach to this question. We would approach a sample of "sister" foundations that were working in science education, to gather data about what their programs target and what they know about their program's effectiveness. We have conducted this study through a review of foundation web pages and other documents, a mail survey, and telephone interviews, and we present the findings of this study in Section 2 of this report. The findings from this empirical study are presented in two forms:

- A profile of the current "landscape" of private foundation funding for science education. For this portion of the study, we selected 37 foundations that are key players in science education nationally or (in a few cases) regionally. In this analysis, we classify and describe the types of educational activities that each foundation supports, based on the responses to our survey and document review.
- An analysis of "best practices" for secondary chemistry education, based on survey and/or telephone interview data from representatives of 16 foundations within the larger group above. In this qualitative analysis, we analyze foundation officers' collective advice on: the arenas where their foundations have chosen to work, and why; the critical elements for strong program design in these educational arenas; and the challenging issues of dissemination and sustainability of effective educational practice.

2) How do foundations assess for themselves "what works" in their science education giving?

The foundations in our sample represent a range of situations with respect to evaluating their own project work, from little or no evaluation work, to increasing guidance for evaluation of the projects they fund, to those undertaking program-level evaluation across the entire set of work that they fund. This diversity of approaches is not a surprise—indeed it was suggested by our initial literature review—but it does indicate the dynamic state of the philanthropic community today, which as a whole is moving toward more active and deliberate evidence-gathering practices, though at different rates of movement among individual programs and across foundations.

Discovering this dynamic state of affairs led us to a new variation of the study question: What kind of evidence can be gathered in the future to assess "what works"? Thus we conducted a separate analysis of the empirical data from the foundation sample to extract information about the foundations' evaluation practices and requirements across their activities in science education. In Section 3 of the report, we summarize our findings on foundations' evaluation practices. In particular, we discuss some case exemplars of innovative approaches to evaluation that may prove useful models for the Dreyfus Foundation in improving the body of evidence that it gathers about the effectiveness of its own work.

3) What do we know about what works in secondary science education, in general?

As we carried out the empirical study of foundations' practices and knowledge about outcomes in science education, it became clear that most foundations in our sample did not have sufficient evaluation data on the impact of their work for us to derive a well-grounded, empirical answer to the research question. We thus elected to support the empirical study with a second study, a review and summary of the educational research literature on a selected group of educational arenas within secondary chemistry education.

Findings from this literature review are provided in Section 4. Our review focuses on arenas—such as curriculum development and teacher professional development—that reflect historical areas of interest to the Foundation and that might be considered as high-leverage targets for future work. Because the review draws from meta-analyses and review articles, most of which are not specific to chemistry but are general to science education, we provide chemistry-specific examples for general areas; we also discuss some areas of the literature that address particular challenges in learning chemistry. Our goal for this review is to provide a user-friendly guide to core principles from the science education literature that might guide the Foundation in its future efforts and provide some benchmarks for assessing future proposals in select arenas.

2 What do we know about "what works" in secondary chemistry education? Findings from an Empirical Study of Foundation Practices

2.1 Research Design and Methods

As discussed, we initially sought to examine what other foundations have learned about "what works" in secondary chemistry education. We anticipated that it might be necessary to broaden this focus, as many grant-making agencies and philanthropic organizations work in science education but do not focus specifically on chemistry education. Second, many grant-making agencies fund a wide variety of programs, some that may specifically address secondary education and some that may address a broader spectrum, including the entire K-12 continuum. Therefore, it can be difficult to identify and isolate specific grants that target secondary chemistry education. Nevertheless, we identified and contacted a broad range of private and corporate foundations and philanthropic organizations to learn more about their funding practices, evaluation methods, and program outcomes. Below we describe in more detail our sampling, survey and interview methodology, and analysis methods for this study.

2.1.1 Sample Selection

We initially conducted an internet search of grants databases to identify private and corporate foundations[1] that appeared to be key players in the arena of science and/or chemistry education. We identified key players both by the amount of their giving and by their focus on chemistry education and/or secondary science education. We created a database that contained, when available, contact information for each foundation, the amount of its science education giving, and the nature of its science education giving.

[1] The National Science Foundation is a significant supporter of science education but was excluded, in consultation with Dr. Cardillo, due to its distinctive mission, size, and resources. A review of the results of NSF-funded activities in secondary chemistry education would be useful but would constitute an extensive task in and of itself.

We also added to the database through "snowball sampling" methods. That is, when we contacted foundation personnel to discuss their own foundation, we also asked which other foundations they thought were key players in chemistry and/or science education philanthropy. We added several foundations to the database through this method. Through phone calls, we also realized that several of the initially identified foundations did not meet our criteria because they did not focus on secondary education or their scope of giving did not include science education. Thus, we concluded the "mapping" portion of our study with a database of 37 foundations to further investigate.

We then distributed surveys to all of the foundations within the revised database. The survey asked foundation representatives to identify individual projects that the foundation had funded in science education for students in grades 7-12, to provide an estimate of the dollar amount of giving, to list the types of activities that were funded, to identify sources of information about the effectiveness of funded programs or projects, and whether they would be willing to participate further in the study. We sent five rounds of surveys to the contacts in our database. The first round of surveys was sent in March, 2006 and the final round of surveys was sent in April, 2007. When we had phone or e-mail contact information, we reminded the foundation personnel to complete the survey.

To increase response rates, we followed specific protocols that have been shown in the research literature to increase survey response rates such as sending multiple rounds of surveys, placing follow-up phone calls or sending follow-up postcards, personalizing cover letters, and sending stamped rather than metered return envelopes (Fox, Crask & Kim, 1988). Nonetheless, we had difficulty obtaining contact information for ten corporate foundations within our sample, despite repeated calls to corporate headquarters and detailed internet searches. Four of these foundations asked that we submit the survey to their "survey response" departments and we never received a reply in return. For others, we were never able to gain specific contact information for a named individual, and, therefore, we sent generic letters to the foundation itself or to the corporate headquarters, depending on the address information available. It is not surprising, then, that we did not receive survey responses from this sub-set of corporate foundations.

Overall, we received 16 survey responses, for a response rate of 43%. This is higher than the typical response rate of 30%-36% for surveys sent to organizations (Baruch, 1999; Tomaskovic-Devey, Leiter, & Thompson, 1994). This response rate is also particularly strong given that we never obtained specific contact information for 27% of the foundations in our sample. Thus, our response rate for foundations for which we had specific contact information was 59%. Of the surveys we received, four organizations declined to participate further in the study for various reasons. Lucent Technologies was undergoing a merger and shifting its philanthropic focus from science education to general education; the Carnegie Corporation of New York was a significant funder of science education in the past but has since revised its funding priorities; a representative from the American Association for the Advancement of Science did not feel that AAAS was a good fit for the study; and the Amgen Foundation did not provide a reason for its decision not to participate.

2.1.2 Interviews

Based on the survey responses, we conducted follow-up interviews with program officers from the remaining twelve foundations that were willing to participate further in the study. The interview protocols addressed the nature of the foundation's science education grant-making, the extent to which its funded programs incorporated chemistry education at the secondary level, the manner in which the foundation set its funding priorities, the decision-making process used to evaluate grant proposals, the evaluation methods used to determine the outcomes of funded programs, and what the foundation staff have learned about "what works" in science and/or chemistry education. We took extensive notes from these interviews and transcribed seven interviews in which the conversations were most productive. Transcription allowed us to conduct more detailed analysis of the philanthropic practices of these organizations. We chose not to transcribe the remainder of the interviews because the foundations had not extensively evaluated their programs and thus the information they provided was of limited utility to answering our study questions. For these latter interviews, comprehensive notes were sufficient for analytic purposes.

2.1.3 Analysis Methods

Our research methods are ethnographic and rooted in the disciplines of social psychology, sociology, and anthropology. We utilized ethnographic data analysis methods for the surveys, interviews and database that collectively represent the data set for this study. To analyze the data, we identified common themes or patterns in responses, tagged them with code names, and clustered them into groups. Codes are not preconceived, but empirical—each new code references a discrete idea. Groups of codes that cluster around particular themes are assigned to domains (Spradley, 1980). This interconnected and branching set of codes and domains allows us to discern distinct patterns among study participants.

2.2 Findings

We first describe a classification scheme for foundations' arenas of activity in science education and present a comprehensive table that lists key players in science education philanthropy and classifies their areas of activity. By demonstrating the areas of science education where foundations do and do not invest resources, this table portrays the current landscape of the nature of philanthropy in secondary science education in the U.S. The information in the table is based on interview findings, survey responses, and internet searches.

We then briefly outline key findings from our interviews with foundation personnel. We describe the nature of their philanthropic activities and the effectiveness of their programs in secondary science education.

2.2.1 The Landscape of Philanthropic Activity in Science Education

In Table 1 below, we have identified major types of philanthropic activities for both private and corporate foundations through surveys, interviews, and internet searches. As might be expected, disciplinary lines and populations served were often blurred. It was often difficult for foundation personnel to tease out programs that specifically addressed chemistry education for secondary students. Thus, we have identified 15 major types of philanthropic activity in general science education. We first describe these 15 types (designated A-O) and then present a table that lists and classifies the program activities supported by the foundations identified as key players in science education. The table thus represents a comprehensive, though not exhaustive, portrayal of the current landscape of science education philanthropy in the United States.

Some caveats to the use of this information are in order. As noted, we could not reach some foundations (particularly corporate foundations) identified as significant funders in this area. We depended on internet searches, grants databases, and foundation personnel themselves to identify key players in science education philanthropy. Though we conducted a comprehensive search, we may have nonetheless overlooked some foundations active in secondary science education.

Table 1 also provides a broad typology of four different types of foundations that are involved with science education. Some focus exclusively on science education while others fund science education initiatives as part of a broader mission. While the majority of these foundations do not have an exclusive focus on chemistry, most, if not all, of them have funded chemistry education initiatives or broader science education programs that have involved chemistry in an interdisciplinary manner. We have divided the foundations into several categories: foundations that focus exclusively on education and research in chemistry; foundations that focus exclusively on science and mathematics education; foundations that support science education as a component of a broader educational mission; and foundations that support science education as a component of a broader general mission. This latter category of foundations may also fund arts, cultural, historical, health, and community programs in addition to educational programs. For the most part, we have only included foundations with a national scope; however, several regional foundations, including the Burroughs Wellcome Fund, the Noyce Foundation, and the Welch Foundation, were included in our sample after representatives from several peer organizations recommended that they were “key players” in philanthropy for science education and/or chemistry education.

To summarize the results of this analysis, the most common philanthropic activity in science education was support for informal educational programs, including after-school programs, summer camps, and museum-based educational activities and programs. Private foundations engaged in this type of philanthropy more often than corporate foundations. Teacher professional development workshops and institutes were also commonly funded, as were scholarships and research fellowships. Corporate foundations funded scholarships more often than private foundations, while both types of organizations funded teacher professional development programs.

Other common areas of philanthropic effort included curriculum development, particularly for school classrooms, and technological projects, such as online resources for teachers. The least common area of giving was classroom projects in which teachers are funded to develop and implement laboratory work, special projects, or inquiry-based lesson plans. Other areas of philanthropy that were less common, but also practiced by some funders, include school district-wide initiatives and efforts to impact policy.

A. Student competitions

Some foundations provide grants for organizations to sponsor science education competitions for middle and high school students. Most often, these competitions involve teams of students who design and build a science or technology project from a standard set of supplies and materials. For example, 3M Foundation, Delphi Foundation and the Motorola Foundation (among other corporate sponsors) provide funding for FIRST (For Inspiration and Recognition of Science and Technology) competitions. FIRST holds multiple student contests such as the robotics competition, where teams of students must solve problems and design robots using the same equipment and a common set of rules. For the most part, student competitions are funded by corporate, not private, foundations.

B. Student scholarships, fellowships, and/or research internships

While many foundations in our database offered doctoral or post-doctoral research fellowships, we have included only support for college scholarships, research assistantships and/or internships in this category. Internships and research assistantships for high school students are also included in this category. Doctoral and post-doctoral awards were excluded because they are too far removed from secondary education and focus on scientific research, not science education. On the other hand, undergraduate scholarships or research fellowships were included because the goal of many of these programs is to provide an authentic science research experience for students and to increase the scientific "pipeline." Scholarships often target pre-college secondary students who may be encouraged to study chemistry and other sciences in high school in order to win a scholarship to pursue their science studies.

Many scholarship programs target high school students. For example, the American Honda Foundation provides funding for the "Students Run L.A." program that provides college scholarships to graduating high school seniors who have completed the Los Angeles marathon. The program also provides grants to students for S.A.T. preparation courses. Some of the programs in this category provide scholarships to individual students while other grants provide funding for extant scholarship programs such as the United Negro College Fund.

The majority of programs in this area do not seem to be science-specific. However, a few corporations do provide individual scholarships to promising science and engineering students. This category is also predominantly populated by corporate foundations, with the exception of the Hach Foundation. The Hach Scientific Foundation is a private foundation that provides scholarships for second-career chemistry teachers. This scholarship program is targeted toward individuals with an undergraduate degree in chemistry who have worked in the field of chemistry, and who have been accepted into a master's of education program to become chemistry teachers.

C. Classroom projects

Classroom projects are not a common focus for funding among science education foundations. However, some foundations provide mini-grants to teachers to implement innovative, real-world science lessons or activities in the classroom. Many of these projects are planned and led by teachers or teams of teachers for use in their own classrooms. The projects are often based on the science in students' daily lives or communities and seek to help students become more engaged in science through the use of hands-on or inquiry-based activities. For example, Toshiba America Foundation recently funded a project in the Detroit area to teach physics using familiar aspects of the automobile. The project also sought to introduce students to alternative energy sources. At the end of the program, students designed and built a solar-powered car.

Toyota USA Foundation also offers TAPESTRY mini-grants to middle and secondary science teachers. For instance, Toyota funded a team of teachers in Pennsylvania to create and implement a curriculum unit called "Coal Mine Chemistry." The project focused on the study of the chemistry of mines and the design of safer mines. Students visited a coal mine, interviewed mine workers and engineers, and designed and conducted scientific experiments. During the course of the curriculum unit, students designed activities about mines for younger students, produced a documentary for the school board, created a safe mines exhibit, and presented their research findings at a Junior Academy of Science meeting.

D. Equipment, materials, and facilities for schools

This category encompasses a broad range of grants. Some grants are directly for school facilities or equipment necessary to improve science education. Other grants are targeted toward the development of science education materials and resources. For example, grants may provide funding for materials and supplies to conduct a class science project or experiment. Equipment and materials grants tend to be smaller in scope than facilities grants. Facilities grants are often used to renovate or build scientific laboratories or classrooms. These grants are typically awarded to individual teachers, schools, or school districts.

E. Technology and online resources

Philanthropic giving in this category is largely focused on the development of science education web sites and web resources, most often targeting specific organizations or programs who develop and implement online resources for science education. However, some foundations have also developed their own online resources. For example, the Chemical Heritage Foundation has created extensive online resources focusing on the history of chemistry.

Other foundations have undertaken technological projects that enhance their own programs or grant-funded projects. For example, the Noyce Foundation has partnered with Agile Mind, a technology company, to create web-based teacher professional development for high school mathematics courses, with the goal of increasing the accessibility of its teacher professional development programs. This category excludes computers for use in the classroom, as computer hardware is included in the facilities and equipment category.

F. Curriculum development

Some foundations provide grants to external organizations to design curriculum units or entire courses, while other foundations develop their own curricula. For example, the Chemical Education Foundation creates its own chemistry curricula for K-8 teachers to introduce basic chemistry concepts to students.[2] The curriculum kits include lesson plans, experiments, a teacher's manual, and an animated DVD, and the experiments all involve everyday, household materials.

The Shodor Education Foundation has also developed extensive curriculum materials for teachers and students that are available on its web site. The focus of the Shodor Education Foundation is to integrate science education with computational science, and some of its resources are high school chemistry-specific. Foundations that fund external organizations to develop curricula typically fund teams of teachers, professional organizations or higher education institutions to design hands-on, inquiry-based lessons and activities to help students learn scientific concepts through a process of discovery.

G. Teacher professional development

In our sample, teacher professional development was the second most common activity undertaken by science education foundations. This category includes both foundations that design and implement their own teacher professional development workshops and those that fund other programs or organizations to develop teacher professional development workshops or materials. For example, the Howard Hughes Medical Institute funds many university-based

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[2] Although not active solely in secondary education, this foundation was included in our sample because its curriculum kits are designed for middle school students and because of its explicit focus on chemistry education.

projects that offer teacher professional development workshops or institutes to increase secondary teachers' content-knowledge and introduce them to inquiry-based teaching methods.

Other foundations support in-house teacher professional development. For example, the Merck & Co. Foundation created the Merck Institute for Science Education to provide intensive professional development in inquiry-centered science teaching methods to teachers and principals in the New Jersey/Delaware area where Merck is active. The foundation has provided a ten-year, $20-million commitment to the Institute, which utilizes inquiry-based methodology and works closely with partner school districts to incorporate science inquiry system-wide. The Institute structure provides for plentiful follow-up with participants through mechanisms such as peer coaching where teachers support and mentor one another during the school year.

H. Informal education programs

The most common philanthropic activity among science education foundations is the funding of informal educational experiences such as museum programs, summer camps, after-school programs, science center and visitor center programs or other science enrichment experiences. This choice reflects the view of foundation personnel, who reported in our surveys and interviews that they felt that they could have greater impact outside of the traditional school system. The size, complexity, and variability of K-12 systems made it difficult to influence science education, thus many foundations viewed informal educational experiences to be more fruitful and productive means of facilitating student learning, and generating interest and enthusiasm for science.

While some of these programs have an explicit emphasis on secondary students, many target K-12 students more broadly. Also, few, if any, of the programs specifically involve chemistry education. Instead, they are often interdisciplinary or focused on general science. For example, the Noyce Foundation funds math and science tutoring programs for inner-city youth and math and science summer camp programs. The Noyce Foundation also funded a dissemination grant to the New York Hall of Science to work with other science museums to replicate its Science Career Ladder program for high school students and undergraduates. The Noyce Foundation has recently shifted its funding priorities to focus more heavily on informal science education. Many corporate foundations also fund informal education programs. For example, Medtronic Foundation funds after-school and summer programs at science museums.

I. School-wide initiatives

This category encompasses philanthropic giving to specific schools for science education purposes. This funding is often targeted toward math/science specialty high schools, but may also include grants to traditional high schools to develop specific math and science educational programs. For example, one of the primary educational missions of the Bill and Melinda Gates Foundation is to transform secondary education in the United States through the creation of small-scale high schools that offer personalized support for students and a rigorous college preparatory curriculum. A few of these high schools have a science and/or technology focus.

The Sloan Foundation has also funded individual member schools of the National Consortium of Specialized Secondary Schools. These grants helped science and technology high schools to recruit and retain more minority students. Individual schools used the funds to hire recruiters, develop summer programs or offer support services for minority students.

J. District-wide initiatives

Although not a common mode of giving, some foundations have supported specific school districts to undertake science education initiatives. These grants often involved support for the creation and/or implementation of science education projects, such as inquiry-centered science activities. For example, the Medtronic Foundation funded several districts to increase and promote opportunities for inquiry-based learning in their science classrooms. The Herbert and Grace Dow Foundation provided funds for one school district to create a math and science center. The Bill and Melinda Gates Foundation has funded many districts to redesign the organizational structure of their schools and transform curriculum and instruction. This latter example is not necessarily science or chemistry-specific, but science programs were certainly impacted by the district-wide transformation of schools and teaching.

K. Policy

Very few foundations reported that they were directly involved with education policy. However, we discovered several ways that some foundations have become involved with policy on a local, state or national level. Though different in nature and scope, these efforts all share a focus on non-partisan or bipartisan collaboration and an emphasis on the use of research-based evidence to inform key educational policy decisions. For example, because of its size and endowment, the Bill and Melinda Gates Foundation is able to influence policy on a national level. The foundation works closely with partner organizations and policymakers in 27 states to increase high school graduation rates and to create more rigorous college preparatory coursework requirements for high school graduation.

Other foundations are involved with educational policy at the state level. The Burroughs Wellcome Fund has focused its science education efforts in its home state of North Carolina. It has influenced state educational policy through several means. It has funded an International Studies Program to help education policymakers learn about effective educational practices in other countries. The program emphasizes international study exchanges involving educators and policymakers. For instance, legislators and educators traveled to England to review the use of school vouchers in that country. As a result of that trip, legislators decided not to further pursue the use of vouchers in the state of North Carolina and to focus on school choice and charter schools instead. The Burroughs Wellcome Fund has also funded the North Carolina Institute for Education Policymakers, which offers briefings for all new legislators and members of the State Board of Education that provide policymakers with research-based evidence on educational best practices. The goal is to familiarize legislators with educational research and to promote bipartisan discussions of education. The foundation also funds external research and policy centers to disseminate educational research.

The Noyce Foundation provides grants to policy centers to disseminate and share educational research with legislators, policymakers, and the public. The foundation trustees and staff have also served in leadership roles for policy advisory groups in their local regions of Massachusetts and California. More recently, however, the Noyce Foundation has moved its focus away from systemic initiatives and has begun to focus on smaller-scale, informal education programs. Finally, the Bristol-Myers Squibb Foundation has funded Teaching and Learning Centers at several local universities to spearhead regional education reform, coordinate and deliver services to educators, and disseminate educational research.

L. Employee volunteerism and donations

We found that volunteerism and donations were only formally supported by corporate foundations. Many corporate foundations promote volunteerism among employees of the parent corporation. Employees are encouraged to tutor in after-school programs, volunteer in local schools, speak to science classes or give presentations or demonstrations to science students. Many corporations also provide matching funds for employee donations to specific non-profit organizations, some of which may be education or science-education related.

M. Special events

Some foundations sponsor special events such as science fairs or festivals or host events such as science education conferences or symposia. For example, the Chemical Heritage Foundation hosts a wide variety of special events: awards ceremonies, lectures, conferences, dinners, and celebrations of historic events. Some foundations, such as the Knowles Science Teaching Foundation and M.J. Murdock Charitable Trust, host conferences for their grantees and/or award recipients. For example, the Murdock Charitable Trust holds an annual conference for its Partners in Science award recipients, which provides research opportunities for high school science teachers.

N. Special projects

This broad category encompasses many different kinds of special projects or programs, including support for science programming on public broadcasting outlets, special science exhibits, or educational research addressing critical issues in secondary science education. The Noyce Foundation is involved with several different types of special projects, providing funding for NPR's *Science Friday* and *Kids' Connection* programming. It also provides support for educational research in key areas of mathematics and science education. The Chemical Heritage Foundation offers special collections and exhibits about the history of chemistry. The Alfred P. Sloan Foundation is involved with archival projects to preserve the papers and letters of Darwin, Edison, and Gödel and has historically funded a broad range of science education research endeavors.

O. Partnerships

Although almost all of the foundations in our sample encourage partnerships to advance science education initiatives, some of them specifically focus their funding efforts on developing effective partnerships including community organizations, businesses, educators, and/or policymakers. For instance, we have already mentioned the partnerships and collaborations that the Bill and Melinda Gates Foundation and the Burroughs Wellcome Fund have developed to shape educational policy. Other foundations have funded collaborations among organizations to develop programs or curricula or address other educational issues. For instance, the Noyce Foundation has funded several partnerships to develop high school biology and chemistry courses, disseminate educational research, or impact school or educational leadership.

Table 1: Foundations Surveyed and Nature of their Science Education Giving

Foundation name (state in which foundation is headquartered)	**Types of Activities Funded**[3]														
	Competitions	Scholarships	Classroom	Equipment	Technology	Curriculum	Teacher PD	Informal ed	School-wide	District-wide	Policy	Employee	Special events	Special projects	Partnerships
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
A. Organizations with an exclusive chemistry education focus															
American Chemical Society (DC)	X	X			X	X	X	X							
Chemical Education Foundation (VA)						X									
Chemical Heritage Foundation (PA)					X		X	X					X	X	
Hach Scientific Foundation (CO)		X													
Welch Foundation (TX)		X													
B. Foundations with an exclusive science education focus[4]															
Burroughs Wellcome Fund (NC)		X						X			X				X
Delphi Corporation[5]	X	X										X			
Howard Hughes Medical Institute (MD)		X		X	X		X	X							
Knowles Science Teaching Foundation (NJ)													X	X	
Motorola Foundation (IL)	X						X	X							
Shodor Education Foundation (NC)		X			X	X		X							
Toshiba America Foundation (NY)			X	X											
C. Foundations with science education as part of a broader educational mission															
American Honda Foundation (CA)	X	X			X	X	X	X	X			X		X	X
Noyce Foundation (CA & MA)					X	X	X	X			X			X	X

[3] See text for details of the categories A-O.
[4] May also include scientific research.
[5] Not currently active in science education.

Table 1, continued...

	Competitions	Scholarships	Classroom	Equipment	Technology	Curriculum	Teacher PD	Informal ed	School-wide	District-wide	Policy	Employee	Events	Projects	Partnerships
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
D. Foundations with science education as part of a broader general mission															
3M Foundation (MN)	X						X	X				X			
Alfred P. Sloan Foundation (NY)					X				X					X	
Amgen Foundation (CA)		X					X	X		X		X			
Annenberg Foundation (PA)								X							
Arthur Vining Davis Foundation (FL)					X	X	X								X
Bayer Foundation (PA)		X							X	X		X	X		X
Bill and Melinda Gates Foundation (WA)		X						X	X	X	X				X
Bristol-Myers Squibb Foundation (CT, NJ, IN, NY)						X	X	X			X				
Carnegie Corporation of New York[4] (NY)						X			X	X	X				
Charles Edison Fund (NJ)		X			X	X			X					X	
Crail-Johnson Foundation (CA)		X				X		X	X						
Exxon Mobil Foundation (TX)					X		X	X				X		X	X
Ford Motor Company Fund (MI)	X	X		X		X	X	X	X			X	X	X	X
Genentech Foundation (CA)		X						X							
Herbert & Grace Dow Family Foundation (MI)				X	X			X		X			X	X	
Lucent Technologies Founation[5] (NJ)	X	X					X			X		X			
M.J. Murdock Charitable Trust (WA)				X			X	X	X				X		
Medtronic Foundation (MN)	X	X		X			X	X	X	X		X	X		
Merck & Co. Foundation (NJ)		X		X			X					X			
Pfizer Foundation (NY)				X		X		X							
Qualcomm Inc Foundation (CA)					X	X	X	X	X						X
Toyota USA Foundation (NY)		X	X	X	X	X	X	X					X		
William and Flora Hewlett Foundation (CA)				X	X	X	X				X			X	
Total Number of Foundations	8	19	2	10	14	15	19	23	11	7	6	10	8	10	9
Percentage of Foundation Sample (%)	*22*	*51*	*5*	*27*	*38*	*41*	*51*	*62*	*30*	*19*	*16*	*27*	*22*	*27*	*24*
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**

2.2.2 "What Works": Best Practices in Science Education Philanthropy

In this section, we briefly outline best practices, or "what works," in science education as identified by foundation personnel through surveys and interviews. Because we were not able to collect extensive information from every foundation representative, we have, to a limited extent, augmented this section with information culled from internet searches of foundation web sites and annual reports, particularly for the section on teacher professional development.

2.2.2.1 Scope and limitations of these findings

As mentioned, we did not identify enough foundations active in chemistry education to make specific recommendations about chemistry education. The chemistry-focused foundations in our sample had vastly different missions and program activities, and many did not provide grants for external programs, making it hard to find commonality across these foundations. However, we could compare practices across science education foundations in general. Many, if not all, best practices in education cut across disciplinary boundaries. Our primary constraint, then, in reporting "what works" in science education philanthropy, was not the lack of a chemistry education sample but the lack of research and evaluation efforts among most science education foundations.

We found, particularly through our interviews with foundation personnel, that many foundations collected minimal meaningful data about the effectiveness of their programs. Most foundations had collected records of populations served and other basic statistics from annual reports, but many did not have information about program outcomes that measure impact on these populations, such as increased student interest in science or motivation to pursue further science education or career opportunities. It was not common for foundations to require research or evaluation reports that compared outcomes of program participants with non-participants to more rigorously assess the impact of a particular program. Even fewer foundations had data about *why* certain outcomes occurred (e.g., what about the program served to increase student interest?). Without these types of data, it is difficult for us as evaluators, and for funders themselves, to determine "what works" in science education philanthropy.

A lack of rigorous evaluation practices is not unique to the foundations within this study. For example, according to a 2005 report from the independent Foundation Center, education received the most money of any area of philanthropic interest, comprising 25% of all foundation giving for the year (Foundation Center, 2005). However, little is known about the outcomes and impact of this spending. There is no mechanism for wide dissemination of the findings from evaluated initiatives. Evaluation studies are rarely accepted for journal publication; no national web site exists to share their outcomes, and reports that do exist gather dust on the shelves of funding agencies. Thus the question of "what works" in philanthropy in science education is a difficult one to address due to the lack of comprehensive evaluation practices among many foundations.

Most foundations within this study required annual reports from grantees and conducted site visits to program locations; however, according to program officers, the quality and utility of these reports was variable. Most foundations reported that few, if any, external evaluations of their grant programs had been conducted, and among those that had been carried out, the quality varied. Therefore, many program officers could provide only limited information about their evidence for the impact of the projects they funded in science education. However, some of their observations, particularly in the case of larger foundations such as the Howard Hughes Medical Institute, are derived from research- and evaluation-based evidence of its grant programs. We were struck by the extent to which the research and evaluation data collected by these foundations aligned with promising practices identified in the educational research literature. Thus, what some foundations have found works in their own programs is also supported in the research literature in education. Below, we have synthesized this information into broader categories to describe promising practices that foundations have identified from their various program activities in science education.

2.2.2.2 Setting directions for grant-making

Although we did not specifically ask foundation personnel how they set the direction for their science education philanthropy, several offered observations in this area. These study participants stressed that foundations should identify areas of critical need in science from the research literature in education. For instance, one representative pointed out that the research literature identifies secondary science teacher recruitment and retention as an area of critical need in secondary science education. Others highlighted the need for better science curricula in secondary schools and greater use of inquiry-based teaching methods in science classrooms and informal educational settings. This program officer noted that curricula are a weak link in secondary science education:

> I think that the College Board studies of AP courses in science said, basically, these courses are terrible. This is supposed to be the equivalent of an early college course, but our college professors looking at them say that they're so broad, and so superficial, that they reduce science to try to cram kids' heads with a lot of facts. And this isn't teaching them what science is about, and it's not really what we want. So I think there's room for curriculum development at the high school level.

One foundation also reported that its leaders had consulted with the National Science Foundation, National Academies of Science, and the American Association of the Advancement of Science to identify critical needs in science education in the U.S. These funding agencies advised the foundation to focus on informal educational opportunities for students because it would yield the greatest impact for the limited amount of money that funder could invest. Two foundations also stated that reports from the National Academies such as *Rising Above the Gathering Storm* could be helpful in identifying areas of need.

Some foundations had also found that addressing one or two critical needs with a concerted effort would yield better results than attempting to address a multitude of needs. They felt that concentrating funding efforts in a region or within a single state could yield more fruitful results and more productive partnerships than trying to address problems on a national level. The success of foundations such as the Burroughs Wellcome Fund in North Carolina provides evidence for this argument to concentrate efforts at the state or local level.

Other foundations, particularly those with strong evaluation efforts, reported that program evaluations could be used to guide funding decisions. For instance, the Bill and Melinda Gates Foundation had chosen to emphasize mathematics education after learning from program evaluations that math education is weak in many schools, even in schools that are otherwise strong.

> I think [our emphasis on mathematics education] came from evaluation of our earliest interactions with schools. We saw, that despite a lot of very fundamental positive changes… that the rigor of instruction wasn't necessarily rising, and where it was rising

> the least, or even not rising at all, was in math—across the board…. So then we decided we would look at some of the schools, districts and networks that seemed to be really highly productive, good schools…. We saw, to our dismay, that they also were not doing as well in math as they were doing in other aspects of their work. So even with the high-performing, top tier of schools that we've been involved with, you're not seeing a lot of success in math. So that sort of universal sense of not being up to par gives us a sense of urgency around this particular subject.

In fact, five of the foundations in our study used evaluation data to determine “what works” in science education and to guide their funding decisions. Program officers from two of these foundations reported:

> We make strategic changes based on the evaluation data that we get back.

> The data will drive you into directions that you probably didn’t think about before. And you have to let the research show you the way.

We draw heavily upon these foundations in our following descriptions of “what works” in science education and project evaluation.

2.2.2.3 Elements of strong project design

When asked “what works” in science education, some foundations, particularly those that had collected extensive evaluation data, discussed the elements of strong project design. For example, the Howard Hughes Medical Institute had conducted a meta-evaluation of the results of all of its grantees’ annual reports and evaluation efforts, to identify key components of successful pre-college science education programs. Staff had identified several components of successful project design that applied to a wide variety of programs in outreach, teacher professional development, and informal education, among others. Having identified these components of success, they now use them as criteria to evaluate proposals and encourage the development of these elements within their funded projects. Some of the findings from HHMI’s meta-evaluation were also echoed by other foundations that had engaged in extensive evaluation efforts. Key findings from this meta-evaluation were published by Felix and coauthors (2004).

The most critical element to successful science education programs identified by HHMI was to have <u>stakeholder support</u> from a broad range of stakeholders. Depending on the project, this may include school district administrators, teachers, students, parents, university faculty and officials, and/or community and business leaders. A program officer from HHMI reported:

> Probably one of the biggest things was having stakeholder support from every possible stakeholder. In other words, if, you’re a science research institution in Boston, and you want to enhance science education in the Boston schools, you need to have some administrators from the school system on board with you. Some teachers on board with you, some students on board with you, some researchers, maybe a local pediatrician, somebody from the local public library. A media person, somebody from a corporation that is hiring kids out of high school or college to do scientific work. And families and parents, And if you can put of all those people together, and get them behind your efforts, it won’t fail.

The stakeholders must be committed to the project and involved with all aspects of the project design and implementation. The contribution of each stakeholder should also be clearly defined.

The HHMI meta-evaluation also revealed that strong projects often began with a needs assessment. In this way, projects could ensure that they truly addressed a real need within the community or given area.

Strong projects are also designed and implemented with clear goals in mind. These goals are linked to specific project outcomes: successful projects have evaluation plans that will provide formative feedback to the project to help it improve and summative data to help the project know whether it is meeting its goals and objectives. Other foundations echoed this recommendation. A program officer from one foundation stated:

> I think that the real important thing is to figure out ahead of time, what do I mean by, "Did it work?" What would convince me that it worked? And can we make sure ahead of time that the systems are in place to tell whether it worked? It goes back to defining those goals, and really thinking about that question of "what would success be?"

Therefore, several foundations recommended that effective projects begin with clear goals in mind and clear methods for evaluating whether they were achieved.

Strong projects also refer to the research literature on education and project development. A program officer from HHMI recommended, "It's important to look at what the current research says about how to design a program that will actually reach students." For instance, if one of the project goals is to improve student learning, then it is critical for the project to consult the research literature on how people learn and to design its activities to maximize student learning. Another program officer stated:

> I think this is such an important piece, on how people learn. The research on that is so clear, and it makes so much sense, and yet I don't think that information has been disseminated as well as it should be [to project developers].

If possible, projects should also involve both scientists and educators. Scientists can provide content-area expertise and teachers can provide pedagogical knowledge. A representative from a foundation that creates its own educational programs and activities recommended:

> Get a wide range of people involved. We've gotten scientists involved, and we've gotten educators involved. Because from each area, you'll get the very intense content descriptions from the scientists, but you'll get the educators who say, "This is above our kids, we need to break it down and make it understandable." Whatever you're trying to accomplish, to just make sure you have a range of people involved, so that you can get the best product possible.

Similarly, another foundation program officer stated, "We've found that it is very important, if you can, to involve a scientist with a program. Because a scientist will bring content knowledge to the table that a science teacher may not be able to bring." Others recommended that if scientists are not available, programs should at least be staffed with skilled science educators.

Finally, effective projects also address sustainability issues. Foundation representatives indicated that projects must address financial planning issues for sustainability beyond the grant and must also make efforts to disseminate their work.

2.2.2.4 Best practices within specific program domains

2.2.2.4.1 Informal education

Most foundation personnel could only report general findings from their funding activities with a variety of projects, many of which were interdisciplinary in nature. Informal education was a top funding priority for many of the foundations in our sample. Foundation personnel reported that working with individual schools or school districts could be difficult and bureaucratic. For practical reasons, they often preferred to fund programs that focused on informal educational settings. One program officer stated, "It's probably best to do something outside of the traditional school day, because it's less bureaucratic on the front end. And we'd be able to have some measurable impact."

Foundations also had other reasons for their preference for informal education arenas. They reported that university-based outreach programs, museums, after-school programs, science summer camps, and science centers were <u>points of high leverage</u> that had greater impact for less investment. Some foundations, such as the Noyce Foundation, preferred to work with informal education because, in their view, the research literature has showed that it is a good way to <u>address "pipeline" issues</u> of student recruitment and retention into science. A foundation representative stated:

> A lot of people who become interested in science, originally acquire that interest, or sustain it through experiences outside of school…. One of our concerns was the pipeline of people who would be the innovators of tomorrow. And so we wanted to find out how, what were ...the experiences that could really spark the interest of young people, and sustain that, even when they didn't necessarily have the best teachers, or the most exciting curriculum in science, throughout all their schooling. It seemed like [informal education] might be a fruitful avenue to pursue.

These speakers indicated that research has shown that informal education can generate and sustain interest in science, particularly during the critical middle school years when students often become disengaged from science. Evaluation data from the foundations themselves also supports this claim. A foundation program officer reported that evaluation data from its informal education programs had demonstrated increased student interest in science: "The students tend to say, 'This was important to me, and it made a difference, and I'm taking more science as a result.'"

However, some foundations, such as the Howard Hughes Medical Institute, also emphasized that informal education programs, like formal education programs, should <u>follow the elements of strong program design</u> outlined above: that is, stakeholder support, needs assessment, evaluation plan, use of the research literature to design the project, the involvement of both scientists and educators, and awareness of sustainability issues. Through their evaluation efforts, several foundations had also found that informal educational experiences are more successful when they <u>incorporate hands-on, inquiry-based curriculum and teaching methods</u>. Students become more engaged and motivated when they are involved with hands-on activities, particularly those that model the process of scientific discovery.

Some foundations also reported that students receive the greatest benefits when they are able to <u>present and share their findings</u> with peers and adults. A program officer reported:

> We suggest strongly, that these programs provide students with an opportunity to communicate their work and present it to others. It helps their communication skills when they're able to stand in front of their parents or colleagues, or people from the community, or people from the program [and] talk about what they've learned, talk about why they thought it was important, and talk about how it impacts them on a personal note…. When a kid talks about what they've done, you get this true sense that these kids really have learned something.

In sum, foundations often recommended that informal education programs follow the elements of strong program design, and that they use effective pedagogical techniques such as inquiry activities and student presentations.

2.2.2.4.2 Curriculum development for school classrooms

Foundations with extensive evaluation efforts reported similar "lessons learned" about successful school curriculum development to those indicated for informal education. Moreover, from their evaluation efforts, these foundations have found that these lessons apply to all scientific disciplines. Although this analysis is not specific to chemistry, these principles certainly apply to chemistry as to other scientific disciplines.

Most of the small sample of foundations with extensive evaluation efforts recommended that curriculum must <u>connect to state or national science standards</u>. Moreover, given the recent political emphasis on assessment, testing, and standards, programs also need to explain to teachers how the curricula align with the standards. A foundation representative stated:

> Science standards are very much an issue at this point. A lot of teachers want to know for each lesson, which standards they cover…. We need to make sure that we're covering the topics that educators need to cover, or at least we're matching up our information with [the science standards].

Aligning curriculum with state or national science standards will increase the likelihood that teachers will implement the curriculum in their classrooms.

Foundations, especially those that developed curricula themselves, reported that it is essential to <u>adapt lessons to be age-appropriate</u>. For instance, a lesson that is targeted to grades 7-12 may not in fact be appropriate for such a wide range of grade levels—it may be too simplistic for the upper grades or too difficult for the lower grades. Therefore, lessons should include tips for adapting the activities for specific grades or should be targeted to a more narrow range of grade levels or to a specific course. A representative from a foundation that creates in-house science curricula commented on data from surveys the foundation had distributed to teachers:

> The main things were just to be aware of the grade levels, that some of the information was over the heads of the younger students, but a little too easy for the older students. Some of them felt the vocabulary that we provided was too simplistic for the older levels, where they could have been challenged with higher vocabulary.

Foundations also reported that the lessons should contain <u>clear directions with illustrations and/or models</u> for the teachers. Finally, there was a broad consensus among foundations that curricula should be <u>challenging and rigorous</u> and incorporate <u>hands-on and inquiry-based</u> activities. A program officer recommended, "Programs must use minds-on, as well as hands-on, inquiry-based activities."

In fact, many foundations stressed that inquiry-based activities were the most essential element of effective curriculum development. To create effective inquiry-based curricula, several foundation personnel suggested that curriculum developers, along with any educational program developer, should consult the research literature on how people learn.

Foundation representatives also suggested that depth of conceptual learning was more important than breadth of scientific facts. Science concepts should be taught through practical applications and real-world activities that demonstrate the science in students' daily lives or communities. Like informal education, many foundations thought that curriculum development was a high leverage area and an essential need for high school science. Most foundations agreed that the majority of high school science curricula is weak, does not encourage strong understanding or retention of concepts, and does not motivate students to want to learn more science. Curriculum development is one way in which to address some of these problems in secondary science education.

2.2.2.4.3 Teacher professional development

As with curriculum development and informal education, foundations that had evaluated their funding activities viewed teacher professional development as a high-leverage activity. One teacher can impact hundreds of students, so it is more economical to train teachers than to try to work directly with students. However, some foundations, such as the Noyce Foundation, have turned away from teacher professional development because it was "hard to demonstrate any lasting impact."

Whether foundations created teacher professional development offerings themselves or funded outside organizations to do so, there was general consensus as to the key elements of effective professional development for teachers. As with curriculum development, foundations reported that it is important to align the workshop[6] content with the curricula that teachers are using in their classrooms and to align the workshops with state and/or national science standards. A program officer stated:

> That's the other thing that we learned from our surveys that was very important, was being able to show how what you are doing is aligned with curricula that high school teachers are using. And explaining how something that, in the current standards, may be amorphous, can be connected to something that isn't amorphous, that's very concrete. We're leveraging our expertise and connecting it to something very practical.

Moreover, professional developers should be explicit in informing teachers as to how the workshop is aligned with the standards.

Teacher professional development should also focus on strengthening teachers' content knowledge and provide them access to recent research and cutting-edge science. However, there was also agreement that the "how" of teacher professional development is just as important, if not more important, than the context or content of the workshop. For instance, an ongoing model of teacher professional development provides more lasting benefits than a "one-shot" workshop. Ongoing models provide follow-up with teachers. Some models, such as the Merck Institute for Science Education supported by the Merck & Co. Foundation, use peer coaching, in which

[6] For simplicity, we use the term "workshop" in the same way that many foundation respondents did, to refer all types of teacher professional development offerings, including courses, professional learning groups, and other forms besides traditional workshops.

teachers support and mentor one another during the school year to implement what they learned from the workshop into their classroom activities. Some models use follow-up workshops or trainings to reinforce teachers' learning, or hold problem-solving sessions throughout the year where teachers can share ideas.

Teachers also need a chance to reflect, share ideas and network within the workshop itself. This helps teachers to develop ideas about their own classroom work and can bridge the gap between teachers' learning in the workshop and their own classroom teaching. Again, foundation personnel stressed that workshop developers should consult the research literature on how people learn and design their workshops accordingly. In this way, workshop presenters can model effective teaching and learning methods for workshop participants.

> How the workshop is designed matters. We've found that teachers get more out of it if they have time to talk with each other about what they learned, and share ideas with each other, for how they may actually use the material in the classroom…. If you want teachers to use inquiry-based methods in their classes, then the workshop should use those types of activities.

In sum, foundations reported that the way in which a teacher workshop is designed and implemented is just as important as the scientific content of the workshop itself. A well-planned workshop will create deeper learning and more lasting change to a teacher's practices than a workshop that has an excellent curriculum but is poorly implemented.

While foundations could report "what works" in professional development in terms of benefits to teachers, they could not easily evaluate the impact of teacher professional development on student learning. The effectiveness of teacher professional development efforts, particularly on student learning, is notoriously difficult to evaluate. Noyce (2006) studied eight exemplary models of teacher professional development that followed the best practices as defined in the educational research literature and found that none of them had collected data that could definitively determine program outcomes. She recommended that teacher professional development evaluation efforts must incorporate several elements: inclusion of a comparison group to track the differences in learning between students of teacher participants and non-participants, the administration of a pre-post test for students,[7] a plan to monitor change in teacher knowledge and action, and the maintenance of careful records to track student and teacher participation. However, these recommendations are challenging to implement, especially on a scale that would yield statistically reliable and valid data. The difficulty of assessing teacher professional development, particularly on student learning, is one of the reasons that many foundations had not effectively monitored program outcomes in this area. Teacher surveys were the primary form of data collection in foundations' evaluation efforts of teacher professional development. Therefore, some foundations could report immediate outcomes from their workshops, but often had not demonstrated longer-term outcomes.

2.2.2.5 Creating lasting change

Several of the foundations that we contacted were interested in creating lasting change within science education. These foundations were more involved with policy and had advice to share

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[7] In our evaluation experience, we have found that administering a pre-post test to students to determine the outcomes of teacher professional development efforts is highly problematic. The study does not occur in a controlled environment and a variety of intervening variables may impact student performance on a given test or measure. Noyce also concedes this point in her article.

for other foundations interested in entering the realm of educational policy. These foundations felt that a systemic approach to education was best, or else as one foundation representative stated, "You're simply making change one school at a time or one teacher at a time." For instance, the Burroughs Wellcome Fund recommended that foundations need to have "lots of structures" in place in order to create systemic change. Foundation personnel involved with policy have also reported that they have achieved greater impact through the creation of long-term partnerships with educators, business, and legislative bodies. A representative from the Burroughs Wellcome Fund commented on its efforts in the state legislature, "It's been one of the best investments of funds that we could have made, because it's making a difference in the policies that [the legislature] are creating for our teachers." Some interviewees also thought that it would be helpful for foundations and philanthropic organizations to collaborate with one another more often.

2.2.2.6 Dissemination

Most foundations thought that it was important to disseminate their efforts and the outcomes of their funded projects, although they have taken varying levels of action in this area. Nonetheless, some foundations were making an effort to post more materials on the web. Many activities can be posted online, such as curriculum lessons and materials, video podcasts of seminars, conferences, teacher professional development workshops, student research presentations or classroom projects, and annual reports. Many foundations expressed a desire to make greater efforts to disseminate their effective activities, particularly on the web, though few had engaged in extensive dissemination of their efforts.

3 "What Works": Best Practices in Evaluation and Assessment of Philanthropic Work

Private foundations and federal funding agencies have expressed increased interest in evaluation in recent years. Though they do not engage in philanthropy in the area of science education, the Robert Wood Johnson and W. K. Kellogg Foundations have been leaders in the area of program evaluation. Their commissioned studies of the evaluation practices of foundations reinforce the findings from this study that foundations are addressing their evaluation needs more frequently, though there is still substantial unevenness (Patrizi & McMullan, 1998; Fine, Thayer & Coghlan, 1998). Similarly, most of the foundations that we studied had collected some information from their grantees about program outcomes, but most had not done so in a rigorous, comprehensive, or uniform manner.

Several authors (Easterling, 1998; Easterling & Csuti, 1999; Chelimsky, 2001; Wilbur, 2005) have called for foundations to not only upgrade the evaluation of their grantees' work, but to use this "grantee-focused" evaluation as one component of a "foundation-focused" evaluation strategy to enhance grant-making, refine their goals, and examine their own organizational effectiveness. Scriven (2000) has argued that "good use of evaluation could often double the payoffs from a foundation's resources," and "there are many cases where a ten times multiplier looks more likely" (p. 1). He also outlines other benefits of evaluation: accountability to trustees and the public; learning from mistakes as well as successes; research that adds to generalizable and specific knowledge, and motivation, saying:

> Without serious evaluation and needs assessment, you have no way of knowing that you are providing help to those who need it most; you have no way of knowing whether what

> you're providing for them is the best you could provide, given your resources; and you have no way of knowing whether the way in which you provide it is anything like optimal—even within the foundation's chosen mission area. (p. 1)

As an example of this approach in practice, the Wallace Foundation has recently made available the results of a self-assessment, including broad measures of its effectiveness in the program areas of its interest (DeVita, 2005). As referenced earlier, the Howard Hughes Medical Institute has also recently published an assessment of the collective impact of 35 of its grants for pre-college science education (Felix et al., 2004). However, these types of efforts are still rare among most foundations. Similarly in our sample, relatively few foundations had heeded this call, and even fewer had disseminated the findings from their evaluations or internal assessments.

However, several foundations in this study had established successful evaluation and assessment programs. Given the relative dearth of objective data about "what works" in science education philanthropy, we offer the evaluation activities of these foundations as interesting models for how foundations can determine program outcomes and impacts. Here we outline the evaluation activities of four case exemplars: the Bill and Melinda Gates Foundation, the Noyce Foundation, the Howard Hughes Medical Institute, and the Burroughs Wellcome Fund. Overall, these foundations emphasize the importance of using evaluation to inform their funding decisions and to guide successful project development. A program officer from one of the exemplar foundations stated:

> I just don't think we can stop or cede or get sloppy about [evaluation]. I think we have to be adamant and thorough and persistent. That strong evaluative and data gathering systems are in place for our investment, no matter what the size. And it's an approach to project development and project management that is not comfortable for everybody. It's also an added expense, but it's well worth it. Because in the end, no matter what the size of your effort, your board is going to look at you and say, "Well, what happened? Did it help?" And the only way you can answer that is through some sort of evaluative structure, and one that has collected, whether it's qualitative or quantitative, the appropriate data. It's not something that, as a sector, we can drop the ball on.

While these four foundations approach evaluation and assessment in different manners, they all share a component of evaluation capacity-building within their models. They have all worked closely with their grantees to help them identify clear, measurable project goals and to implement appropriate measures of those goals. In that respect, these foundations are in the vanguard of program evaluation in their work toward "evaluative thinking" and capacity-building among their grantees.

A few other foundations outside the science education arena also provide evaluation guides or tool kits to their grantees (Kellogg Foundation 1998; United Way, 1996), but these practices are not widespread. In addition, the National Science Foundation has been a leader in developing evaluation capacity in its grantees through its publications and workshops (Chubin, 1995). In fact, several participants in our study recommended the W. K. Kellogg Foundation web site and the National Science Foundation's *User-Friendly Handbook for Project Evaluation* (Stevens et al., 1993) as useful resources to help program officers understand the purpose and process of evaluation and to help grantees develop effective evaluation plans.

3.1 Performance Tracking and an Internal Evaluation Team: The Bill and Melinda Gates Foundation

Because the majority of educational philanthropy at the Bill and Melinda Gates Foundation focuses on school-wide initiatives, that foundation has begun to create a comprehensive "Performance Management Tracking System" for all its grantees. This database will contain specific data for each school such as attendance rates, rates of graduation and college attendance, and so on. A program officer from this foundation stated:

> We have, in the works and not quite completed yet, but about to be completed, a performance management tracking system for schools that we invest in. So we're looking at trends in attendance, graduation rates, course rigor…. What we're interested in learning is what they've been able to accomplish and how they've been able to improve graduation and college-going rate. Those are two outcomes we're interested in with these schools.

In this way, the foundation can compare outcomes across measures and determine whether schools have made progress in areas of interest to the foundation. While this is a vast undertaking given the scope of its activities, smaller foundations may also monitor performance across grants by identifying standard measures that may be collected and tracked across all grants of a specific type.

The Bill and Melinda Gates Foundation also has an internal evaluation staff to evaluate clusters of grants. For instance, the team recently evaluated a cluster of grants in the state of Texas because the foundation funded a large network of schools in that state. The evaluation team uses both quantitative, statistical measures and qualitative methods, such as interviews and focus groups. The evaluation team compares both formative[8] and summative[9] findings from annual reports, external evaluation reports, and other sources to determine the effectiveness of the grants. However, few foundations have the resources to support an internal evaluation team. In-house evaluation offices that conduct studies or advise grantees currently exist only in the largest of foundations (Patrizi & McMullan, 1998). Nevertheless, as we will discuss later in the report, the Burroughs Wellcome Fund has outsourced its evaluation needs to an external evaluation team and has achieved similar results for a fraction of the cost.

Although the Bill and Melinda Gates Foundation has instituted many summative measures to determine the overall impact of its funding, a program officer admitted that the foundation does not currently have a strong system in place to capture formative information that may help grants adapt and revise their programs along the way. However, the foundation does provide capacity-building assistance to grantees to help them develop and implement rigorous evaluation plans of their own so they may collect formative information themselves.

3.2 External Consultants to Develop Common Evaluation Instruments Across Projects: The Noyce Foundation

The Noyce Foundation is currently redirecting its philanthropic activities in science education to focus on informal educational experiences. However, foundation personnel conceded that they

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[8] Formative evaluation is used to identify the processes through which certain outcomes occur. Formative evaluation results are generally used to guide programmatic decision-making and improvement.

[9] Summative evaluation typically involves outcomes measures and can be used to determine program efficacy. The Performance Management Tracking System is an example of a summative data collection system.

need a better way of assessing what works in their funding activities. To that end, they have hired a university-based educational researcher and evaluator to conduct a literature review of survey instruments that may be used to evaluate the impact of informal educational experiences on K-12 students. Through this literature review, foundation staff will see what is available for use with their grantees and also identify gaps where instruments need to be developed for assessment. They have a particular interest in instruments that can be used to assess broad program outcomes of informal education, such as student motivation to pursue more science opportunities, student interest in science, and development of career interests in science.

Once the foundation has developed a database of existing and new instruments, its grantees can use the instruments to assess student outcomes. While this is a time-consuming endeavor, the foundation will be able to use common measures to compare outcomes across programs and to better identify "what works" in its funding. In our interviews, other foundations also spontaneously raised the point that a collection of instruments to evaluate program impacts would be beneficial. A program officer from another foundation stated:

> What I wish I could do better is point [grantees] in the direction of actual tools that they can use. Some of them have these student satisfaction surveys… and some are better than others…. And it doesn't seem to make sense for everybody to be out there re-inventing the wheel, when somebody's got one that you can just tweak and use yourself. And student interest inventories, there are a bunch of interest inventories out there that they can use to see if kids are interested in science—if they're more interested now than when they started with the program, or not. But what I don't have is a very organized collection of those kinds of tools, to be able to point people to.

Currently, to evaluate its programs, the Noyce Foundation collects annual reports from its grantees and conducts site visits. Some of their funded projects have hired external evaluators while others have not. The foundation encourages grantees to determine their project objectives ahead of time and to identify ways to measure them given the resources at hand. The foundation encourages grantees to identify measurable benchmarks and to find appropriate ways to measure whether they have met their objectives. To this end, this foundation's development of a collection of assessment instruments for informal science education will enhance the evaluation efforts of its grantees.

3.3 Capacity-Building and Peer Coaching: Howard Hughes Medical Institute

Program evaluation is a significant emphasis of the Howard Hughes Medical Institute. Like the National Science Foundation, HHMI requires projects to include evaluation plans in their proposals. HHMI has also conducted an extensive review of outcomes across projects. Through this effort, HHMI staff were able to not only identify elements of effective science education programs, but also to identify elements of effective program evaluations. A program officer from HHMI stated:

> We've got all these different projects out there, and they're all different, and they're all evaluating different things. But there's certain pieces of evaluation that are common to everybody, and that any program ought to think about, and questions they ought to answer up front, before they start even trying to evaluate what they're doing. Although all programs are different, there are pieces of evaluation that any program should think about and address.

As with other foundations, a program officer at HHMI recommended that programs must "find a goal, define it, figure out how to measure it, and use evaluation to revise the program."

To this end, HHMI has engaged in capacity-building with its grantees to help them define measurable goals and to develop appropriate evaluation plans. HHMI provides projects with the "vocabulary and techniques" to design a strong evaluation plan. Program officers also provide support along the way to help projects define their goals and to implement and revise their evaluation plans. A program officer stated:

> Part of what I think we give to our grantees that's so important, is just the charge to really seriously think about their own goals. And define as clearly as possible the goals they have for the program that they're running, and then find ways to measure whether or not they're reaching their goals. That part alone has been worth its weight in gold, because so many of them really didn't think about that, they just thought they had a good idea, and thought it would be fun, or they had the resources to do it. And they would go off and running without any real goal in mind.

HHMI does not require that grants have external evaluators, although some grants do hire external evaluators. HHMI staff have found the quality of external evaluation to vary, though a skilled evaluator can be an enormous asset to a program. HHMI also works with external evaluators to "let them know what kind of information is helpful and what isn't." HHMI personnel strongly believe that evaluation is essential to the success of a project, particularly if it is embraced by the organization and used to improve the project.

HHMI also engages in capacity-building with grantees through efforts designed to assist their grantees in helping each other. The foundation encourages grantees to share ideas with each other and support one another in program evaluation efforts. The foundation encourages its programs to share measures because many instruments may be used by programs with similar goals. Grantees work together in groups of four and conduct site visits with one another to discuss program evaluation. One program will host the others who will act as consultants and provide advice to the host. HHMI also brings all of its grantees together every few years to engage in professional development and capacity-building in program evaluation.

Due to its strong efforts in capacity building in evaluation, HHMI had compiled a wealth of information about "what works" in science education. This foundation had engaged in extensive "meta-evaluation" of its programs by synthesizing the results of all of their annual reports and program evaluations. In this way, staff had attempted to assess what has worked across a variety of programs. This also gave them the opportunity to assess the strength of evaluation plans across a variety of projects. They found that there are a wide variety of ways to measure the same phenomenon, such as increase in student interest in science. Instead of mandating that projects use a specific measure, program officers assess whether the measures used by their projects are reasonable, and if not, they work with grantees to develop and implement more appropriate measures. From this type of program-level evaluation across a range of projects, they identified elements of strong, effective projects and improved the evaluation efforts of their grantees.

> What we learned from that is that there are some things that cut across all of our programs. And we then went and changed completely the evaluation pages of the form that we have them fill out every year, their annual report. And we encourage them to use some of the measures that other folks are using, if they're doing the same thing. So it

> helped us to find out what people were doing out there, and find some commonalities among programs and evaluation plans, and then mold our requests for information around that. So that we can now track in a pretty organized manner what people are measuring and how it's going.

HHMI also encourages projects to use objective measures to assess their project's outcomes. Rather than simply documenting "feel-good" outcomes such as enjoyment of the project, HHMI encourages programs to use more specific metrics. For instance, if one of the program goals is to increase student interest in science, HHMI recommends that evaluation efforts track actual, measurable student behaviors such as enrolling in more science courses or joining after-school science clubs. However, HHMI also emphasized that there are a variety of ways to measure outcomes. Therefore, projects and evaluators need to think carefully about their goals and how to best measure them. In sum, HHMI works closely with its projects to help them design and implement rigorous evaluations. They also encourage projects to collaborate and support one another's evaluation efforts.

3.4 Capacity-Building and an External Evaluation Team: The Burroughs Wellcome Fund

Like the other case exemplar foundations, the Burroughs Wellcome Fund engages in extensive efforts to build capacity in evaluation among its grant recipients. Many of the foundation's grantees cannot afford to hire external evaluators and have little or no knowledge of project evaluation themselves. To address this problem, the Fund hires external evaluators, paid for by the foundation, to consult with its grantees. The evaluation consultants constitute 1% of the fund's annual budget. A program officer reported:

> We have a good partnership, and it works out really well. Our program directors and awardees really value having access to this expertise, that they don't have to pay for. And the cost to them would be very high, some of them. Because you've got everything from a university program to a Girl Scout, community-based program. And some of these small community programs just don't have the resources, or access to resources. So that's a big gap. So, what we try to do is level the playing field, and just to make sure that they all have access to the same things.

The foundation holds a workshop for all new grantees to teach them about project evaluation. The external evaluation consultants lead the workshop and work with the programs to help them think about their objectives. The evaluators teach the projects how to create a logic model, an organizational flow chart that documents the area of need served by the program, the specific activities that will address that need, and the anticipated short- and long-term outcomes of those activities.

The evaluators then train project staff in how to develop an evaluation plan. From the logic model, project staff can outline measurable goals and identify ways to collect data to provide appropriate feedback about the performance of the program. The external evaluators teach the project staff how to collect such data and how to use the data to revise their activities. The evaluation consultants may also analyze data for projects if it is beyond the project's capabilities to do so. The external evaluators synthesize the findings from the various project evaluations and present an annual report to the fund. Therefore, the Fund can assess what works across all of their funding initiatives. A decade ago, Patrizi and McMullan (1998) reported that in-house evaluation offices are currently found only in large foundations. However, this external evaluation model may be growing in popularity, as it is a cost-effective way of supplying grant recipients with evaluation expertise and improving program evaluation efforts among grantees.

In sum, these four case exemplars demonstrate that some foundations working in science education have begun to develop creative approaches to the challenge of determining the effectiveness of their giving, through implementing their own program-level evaluation and through fostering better evaluation practices among their grantees.

4 Best Practices in Chemistry Education: Key Findings from the Chemical Education Literature

In this review we briefly summarize several bodies of literature that address some of the educational arenas of interest to the Camille and Henry Dreyfus Foundation. The scope of the review is consistent with the scope of the empirical study of foundation practices and knowledge—that is, focused on formal chemistry education in the secondary grades (6-12). The evidence reviewed here includes findings specific to chemistry education and other findings that are general across science education. Though “chemistry” is not always a distinct topic in K-12 education, chemical concepts are generally included under “physical science” at the middle school level, and chemistry typically emerges as a distinct course in grades 10-12. Topics addressed in this section include:

- Issues in secondary chemistry education;
- How people learn;
- Promising practices: teaching and learning, instructional materials;
- What’s hard about learning chemistry?
- The special role of laboratory work in chemistry;
- Teacher professional development;
- Informal science education.

Each of these topics is addressed below. Our goal has been to summarize the educational research literature and to offer some key ideas distilled from it that may be useful for the Foundation to consider as guidelines for proposers or review criteria, should it choose to focus giving in any of these arenas.

Because educators, like chemists, use a specialized vocabulary, a glossary of selected terms commonly used in chemistry education (and science education at large) is included as Appendix 7.1. In addition, we note that a forthcoming book edited by Stacy Bretz and published by the American Chemical Society will address “Chemistry and the National Science Education Standards.” This is likely to be a very useful resource for the Foundation. We contacted several of the contributing authors but were unable to draw on their work for the purposes of this review.

4.1 Issues in Secondary Chemistry Education

The state of US science education has been much lamented in recent years. The science performance of American 8^{th}-graders on the Trends in International Mathematics and Science Study (TIMSS) has improved since 1995 (NCES, 2005). However, American students continue to rank as mediocre in this international assessment. For instance, in 2003 the US was 14th out of

33 countries in math and science achievement. Scores in physics and chemistry are below those in life science (AAPT, 2005). The TIMSS video analysis of science classrooms across an international sample suggests some causes of these differences: for example, American teachers tend to emphasize procedural skills rather than concepts. Indeed, American science curricula have been famously criticized as "a mile wide and an inch deep."

Young children tend to like science and do well in it; evidence of problems in US science education surfaces at middle school. For example, US fourth-graders rank higher, in comparison with other nations, on TIMSS assessments than do eighth-graders (Gonzales et al., 2004). On the PISA assessment of science literacy, given to over 400,000 15-year-olds in 57 countries, US students rank below the European average (OECD, 2007).

Though two-thirds of young children—boys and girls alike—say they like science, gender differences in attitudes and interest in science also become apparent in middle school (AAUW, 1992; NSF, 2007b). Some indicators of the gender gap suggest that it is beginning to close: for example, girls now take as many high school science courses as boys, and they perform as well (AAUW, 2004). But many girls who take advanced science courses in high school do not continue to study science in college, leading to persistent gender gaps at higher levels of education (De Welde, Laursen & Thiry, 2007). The exact shape of this "leaky pipeline" in science is highly variable by field. In chemistry, women are near parity with men among those earning bachelor's and master's degrees, but their proportion declines to just over 30% of Ph.D.-earners (NSF, 2007a). People of color are still highly underrepresented: in the physical sciences, 8.6% of BS degree earners are Asian or Pacific Islander, 6.7% Black, 6.2% Hispanic, and 0.5% Native American (NSF, 2007a).

Recent work by Robert Tai and Philip Sadler on students' preparation for the study of college science sheds some light on how, in particular, secondary science education may be failing students. These authors surveyed over 8400 first-year college students in 122 introductory college science courses targeted to STEM majors. They asked students about their high school science coursework and learning experiences, then compared students' responses with their college science grades. They found that college science course performance was correlated with the highest level of high school mathematics they had taken. Success was also correlated with prior exposure to the same science subject (Sadler & Tai, 2006), but *not* with advanced work in that subject (Sadler & Tai, 2007a). That is, taking any high school chemistry course led to better student success in college chemistry than taking no chemistry, but taking Advanced Placement (AP) chemistry in high school did not significantly increase students' college success in chemistry. Nor did students' college success increase if they had taken other high school science subjects, for example physics. As Tai and Sadler (2007b) point out, their study offers no evidence to support current proposals to reorganize the high school curriculum in a "physics first" or "biology last" sequence of the types that have been promoted recently (Sheppard & Robbins, 2006; Bardeen & Lederman, 1998).

Because so many college students take introductory chemistry, Tai and Sadler were able to break some results out for chemistry in particular. Based on data from 3521 survey respondents who had taken college chemistry courses, these researchers found that covering specific chemistry topics in high school was *not* correlated with greater college success—with one exception, the topic of stoichiometry (Tai, Ward & Sadler, 2006). Chemists will recognize the importance of this topic, as a strong conceptual foundation in stoichiometry underlies many advanced chemistry topics such as thermochemistry, equilibrium, and kinetics. However, the low relevance of high school chemistry topics other than stoichiometry to college success is consistent with critiques of the "mile-wide, inch-deep" US science curricula: by covering too many topics, deep understanding of any topic is not achieved. A survey of high school teachers (Deters, 2006) confirms that chemistry teachers are as subject as other teachers to over-stuff the high school curriculum.

Though high school course *content* had relatively little impact on college grades, some high school *teaching practices* did affect them. Success in college chemistry was positively correlated with high school courses that included opportunities to repeat lab work; peer teaching and group work; and experience with "everyday" examples of chemical phenomena (Tai & Sadler, 2007; Tai, Sadler, & Loehr, 2005). These practices emphasize conceptual understanding and laboratory problem-solving over mere verification of accepted principles, student construction of chemical explanations, and sense-making through connection to familiar ideas and relevant, real-world examples. However, other common high school teaching practices correlated with lower college performance, including lab work that emphasized following procedures, problem-solving by individual students, and frequent use of demonstrations. While these latter practices are not inherently problematic, in this study they serve as markers for teacher-centered teaching practices that do not have students working with evidence and giving chemical explanations. These findings suggest that effective teaching and learning practices trump content coverage in high school chemistry courses.

Tai and Sadler's findings are echoed by a report from the National Research Council on advanced chemistry courses in high school, particularly Advanced Placement (AP) and International Baccalaureate (IB) courses (Stanitski, 2002). The NRC panel identified desirable features of such courses then compared this wish list to the present situation. They concluded that most advanced high school courses did not have the desirable features they sought: extended content and applications; use of modern methods, instrumention, mathematics and technology; integration of concepts within and between chemistry subjects and with other disciplines; use of inquiry and experimentation; development of critical thinking, communication, and teamwork skills; and assessment strategies that reflect current best practice (pp. 2-6). The panel found that most AP and IB courses emphasized breadth of coverage at the expense of depth of understanding, laboratory work, and higher-order thinking skills. Pressure from parents, students and school boards to offer AP courses often spawns content-heavy courses that focus on exam preparation rather than learning. "Thus, an overarching, largely unintended, but nevertheless real and perverse effect is that the exam-driven nature of both programs may cause the development of intellectual curiosity in students to fall victim to the pace of the courses—all in the name of 'rigor'" (pp. 3-6).

Collectively, these findings suggest some principles that the Foundation may wish to consider as undergirding its future work in secondary chemistry:

- Secondary chemistry courses should emphasize active learning, critical thinking, and collaborative work.
- Laboratory work should be modernized in methods and technology but, most importantly, should emphasize investigation.
- Students benefit most from a solid conceptual foundation in chemistry. When advanced or current topics are taught, these topics should be chosen to build on and enhance fundamental concepts.

- Designations of AP and IB courses do not guarantee high-quality teaching or learning. Other types of advanced coursework in chemistry may serve students better.
- Secondary chemistry education may fail in particular to meet the needs and interests of girls, students of color, and students of low socioeconomic status.
- The Foundation may be well placed to play a leadership role in policy and action to encourage thoughtful investigative work in advanced high school chemistry courses, rather than an emphasis on exam preparation.

4.2 How People Learn

Advances over the past two decades in cognitive science and education research have led to a growing understanding of “how people learn.” Here we summarize three key ideas that emerge from this body of research (Bransford et al., 1999). The implications of these ideas for instruction in chemistry classrooms are discussed in later sections.

1. *People do not come to learning as “blank slates”—they have prior knowledge from everyday experience that they apply to understanding new ideas.* When their prior knowledge contradicts a scientifically accepted idea that they are asked to learn, people may develop and hold simultaneous contradictory conceptions, thus building separate frameworks of “school knowledge” and “real knowledge.”

   In the literature, these prior ideas are referred to as “preconceptions,” “misconceptions,” or “alternative conceptions.” Significant bodies of research literature have catalogued misconceptions and investigated their origins for chemistry as well as for other disciplines. For example, one persistent misconception in chemistry is that when water boils, the bubbles are composed of oxygen and hydrogen gas (Schmidt, 1997; Horton, 2004). This misconception may stem from misunderstanding of several basic chemical concepts, including phases of matter and the difference between chemical bonding and intermolecular forces.

2. *People need to actively construct knowledge by linking ideas into a conceptual framework.* Two aspects of this principle from research are important: First, a conceptual framework is a mental organization of concepts. Concepts linked into a framework are more easily retrieved and more readily applied to new settings than are detached facts. Experts have more efficient and useful frameworks than do novices. For example, when sorting mechanics problems, physics faculty sorted them into a small number of categories based on the underlying concepts needed to solve the problem—conservation of energy, conservation of momentum, and so on. In contrast, first-year college students were easily distracted by superficial features, sorting problems into “inclined plane problems”, “pulley problems”, and so on (Chi, Glaser, & Rees, 1982).

   In a similar study, organic chemistry students were asked to organize terms on a concept map, which is a diagram that shows a visual representation of the relationships between ideas. Students constructed shallower, less complex maps at the start of the course than at the end (Nash, Liotta, & Bravaco, 2000). Moreover, the complexity and richness of students’ final concept maps correlated with their course grade. Overall, students’ concept maps reflected a more novice-like conceptual framework than did their professors’ maps. For example, students more often grouped terms by surface similarity (e.g., linking σ electron and π electron) than did faculty, who grouped conceptually related terms, such as σ electron and single bond, in a more hierarchical structure.

Second, learners must construct the conceptual framework for themselves by actively working to understand and articulate concepts and relate them to one another. Thus, no matter how superb a lecturer he is, an expert's framework cannot be transferred intact to his students' minds. The teacher's task is to help students formulate and refine their own ideas to more closely resemble the scientifically accepted concept. Educational approaches that incorporate this research-based principle are often referred to as "constructivist" approaches. Though schools of education debate the particular meaning of various flavors of constructivism, science educators generally use the term in a broad and encompassing way to refer to student-active teaching and learning approaches. The job of a constructivist instructor is sometimes described as that of "guide on the side" rather than "sage on a stage."

3. *People need to reflect on their learning as they learn*. Reflection on one's own learning, or "metacognition," helps learners to develop effective learning approaches, re-use effective learning approaches that they have used in the past, and relate concepts to what they know already. Metacognition aids in recognizing and abandoning unproductive or naïve ideas (i.e., misconceptions), in developing problem-solving skills, and in organizing ideas into conceptual frameworks, and thus in retaining and applying knowledge (Rickey & Stacy, 2000). Thus fostering metacognition is useful both in learning specific content, and in learning how to learn more effectively—a crucial lifelong skill in the 21st-century Information Age. Many instructional approaches have been developed that seek to encourage student metacognition—thinking about one's own thinking—and have been shown to improve student learning (Schraw, Crippen & Hartley, 2006; Tsai, 2001; Rickey & Stacy, 2000).

4.3 Promising Practices: Research-Based Teaching and Learning Strategies

A growing body of research demonstrates how these fundamental principles of "how people learn" can be translated into classroom teaching practice and supported by good instructional materials. As Springer and colleagues put it (Springer, Stanne & Donovan, 1999, p. 21), "What students learn is greatly influenced by how they learn." In general, these practices may be referred to as "constructivist" or "inductive" teaching practices that support "active learning" or "interactive engagement." "Hands-on" activities are engaging to students but insufficient for real learning; teaching and learning approaches must also be "minds-on." "Inquiry" teaching and learning methods refer to methods that foster learning through mirroring the scientific process: posing a question; gathering and analyzing evidence; constructing, comparing and communicating explanations.[10] Students thus build new knowledge for themselves in a manner similar to the way scientists build knowledge that is new to all. A useful summary of many of

[10] The term "inquiry" has an unfortunate double usage in K-12 science education. Inquiry refers to both a content area—something children should learn—and a teaching and learning strategy—how they should learn. The National Science Education Standards (NSES) (NRC, 1996) distinguish these clearly: the science *content standards* include standards that designate the abilities and understandings of inquiry that children should develop in school: "learning to do" science, and "learning about" science. These are separate from "learning science," that is, the big ideas and key facts of science, which are also part of the content standards. Inquiry *teaching and learning strategies* include approaches to teaching that mimic the process of science. In the NSES, these are part of the teaching standards. In our observation, the latter use is more common. Teachers' awareness of the inquiry content standards, particularly the understandings of inquiry and the nature of science, is often low (Laursen, 2006).

these practices, including teaching and learning approaches referred to as case-based, problem-based, guided inquiry, and just-in-time teaching, can be found in Prince and Felder (2007). Among the more powerful pieces of general evidence in favor of active learning is Hake's (1998) meta-analysis of college and high school physics courses. Across some 6000 students in dozens of courses, a wide range of "interactive engagement" methods led to substantially greater learning gains on a common, discipline-validated, concept test, as compared to traditionally taught courses.[11]

Among the most-well studied strategies for active engagement of students is cooperative learning, also called "collaborative learning" or "small-group instruction". Indeed, this approach is so well-studied that its effectiveness is nearly a truism—yet not, unfortunately, as widely applied. In chemistry, there has been substantial interest in this method; perhaps it appeals to chemists who are accustomed to working in professional teams. Well-designed cooperative learning approaches have positive impacts on student achievement, persistence, and attitudes at both pre-college and college levels (Johnson & Johnson, 1989; Springer, Stanne & Donovan, 1999). Cooperative learning is widespread at the elementary and middle school levels, but less often practiced in high school and college science courses, though also effective there.

However, as Hereid (1998) points out, cooperative learning is not just "throwing students together and expecting learning to occur" (p. 553). Johnson and Johnson (1989) have detailed the essential features of the learning task, group structure, accountability, and group skills that are needed to implement cooperative learning successfully. Bowen (2000) conducted a meta-analysis of studies of cooperative learning in college and high school chemistry classes. Of the 15 studies that reported effect sizes and thus could be included in the quantitative analysis, 11 reported positive impacts of cooperative learning relative to each study's comparison group; the other four studies showed smaller, negative effect sizes. Nurrenbern and Robinson (1997) compiled an early bibliography of chemistry-specific cooperative learning resources; an updated, chemistry-focused resource on this teaching and learning approach was not located.

There is some evidence that cooperative learning benefits women and minority students in particular (Tobias, 1990; Treisman, 1985; Hereid, 1998; Springer, Stanne & Donovan, 1999). Initial performance gaps have been commonly observed for these groups, and members of these groups are more put off when they encounter poor science teaching than white males (Seymour & Hewitt, 1997). Thus the use of cooperative learning tends to close gender- and ethnicity-linked achievement gaps without harming (and often benefiting) white male students who may also be successful without cooperative learning.

The application of educational technology to learning chemistry has also been of substantial interest to chemical educators. Computers aid visualization of microscopic processes through modeling, simulations and animations and thus seem to many chemists a "natural" tool for learning, in addition to their general scientific use for data analysis, graphing, communication, and other functions. Modern computers can compute physically accurate, real-time simulations of molecular dynamics that include not only gas kinetic behavior but the intermolecular

[11] Hake (1998) defines interactive engagement (IE) courses as those making substantial use of methods "designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors." Traditional courses are thus those that "make little or no use of IE methods, relying primarily on passive-student lectures, recipe labs, and algorithmic problem exams."

interactions that yield phase changes and chemical reactions (e.g., Xie & Tinker, 2006). While many published articles report the results of assessments of specific technological tools for science learning, including chemistry (see Bell & Bell, 2003), we were unable to locate a good review or meta-analysis that summarized the evidence on the impact of educational technology on chemistry or science learning for K-12 students. This may be due in part to the fact that educational technologies evolve rapidly; the current literature rarely reflects the power and potential of current software and hardware. And, as Bell and Bell (2003) note, articles on educational technology are not frequently published in the journals that science educators read, but in technology-oriented journals—thus awareness among science educators of this literature is low. Our search efforts lead us to conclude that, while a number of specific technology applications have demonstrated positive results, in general, it appears that the learning benefits from classroom technology use are highly dependent on the pedagogy that is embedded in the technology use (e.g. do students practice routine problems, or conduct highly interactive investigative work?) and the context in which they are used. Thus it is difficult to separate the impact of technology from other factors, such as whether students work with the technology alone or in groups, which may itself account for positive effects.

Distance learning is a particular application of educational technology that is argued to provide access to learning for students with a range of needs, flexibility in the speed and schedule of learning, and chances for greater parental involvement. Cavanaugh et al. (2004) conducted a meta-analysis of studies of the outcomes of distance learning for K-12 students and found that the results were "ambiguous." While distance education could have the same effects on learning as traditional instruction, it was highly context-dependent, and no particular factors could be correlated with significant positive or negative effects.

Table 2: Relating Key Findings from *How People Learn* to Instructional Materials and Teacher Professional Development
(adapted from Bybee, 2002, p. 139)

	Key findings: **Students…**	Key findings: **Teachers must…**	As a result, instructional materials & teacher professional development must…
1	Come to class with preconceptions	Recognize preconceptions and adjust instruction	Include structured strategies to elicit and challenge student preconceptions Incorporate background for teachers about common misconceptions
2	Need to develop a deep factual understanding based in a conceptual framework	Understand the content and conceptual framework for a discipline Provide examples for context	Organize ideas around an explicit conceptual framework Connect factual information to the framework Provide relevant examples to illustrate key ideas
3	Set goals and analyze progress toward them	Provide class time for goal setting and analysis Teach metacognitive skills	Make learning goals explicit Integrate metacognitive skill development into content

Table 2 summarizes the implications of these cognitive science research findings (Bransford et al., 1999) for teacher classroom practice and for the design of materials and programs to support classroom practice, through instructional materials for students and professional development for teachers. As the table implies, educators' understanding of how students learn is further advanced than our ability to help teachers implement these principles effectively in classrooms.

4.4 Promising Practices: Research-Based Instructional Materials

Curriculum development is one potential target of programs to improve chemical education. Kesidou and Roseman (2002) reported the results of a review conducted about a decade ago by the AAAS' Project 2061 of nine widely used middle school science curricular programs. This review rated most programs as significantly flawed. Key ideas were generally present in the programs, but often buried in details or even unrelated ideas. Programs only rarely "provided students with a sense of purpose for the units of study, took account of student beliefs that interfere with learning, engaged students with relevant phenomena to make abstract scientific ideas plausible, modeled the use of scientific knowledge so that students could apply what they learned in everyday situations, or scaffolded student efforts to make meaning of key phenomena and ideas presented in the programs" (p. 522). While their review has been criticized as overly harsh, the general point of Kesidou and Roseman's review is well taken: curriculum is a crucial but often flawed aspect of good science instruction at the secondary level. Moreover, this problem cannot be solved well at the local level: Most teachers do not have training in curriculum development. Teacher-developed curricula are seldom as well-rounded and conceptually deep as well-developed materials from projects led by chemists and educational specialists. Rather, teachers should be engaged in analyzing curriculum so that they learn to recognize good materials, and identifying clear instructional objectives that help them select appropriate learning materials, use them well, and assess student learning appropriately.

Table 3 summarizes shifting emphases in instructional materials that are consistent with the research evidence on learning and with state and national science education standards.

Table 3: Shifting Emphases in "Reform" Science Instructional Materials
(adapted from the *National Science Education Standards* (NRC, 1996))

Less emphasis on…	More emphasis on…
Focusing on student acquisition of information	Focusing on student understanding and use of scientific knowledge, ideas, & inquiry processes
Asking for recitation of acquired knowledge	Providing opportunities for students to engage in scientific reasoning, discussion, & debate
Assessing scientific knowledge	Assessing scientific understanding & reasoning
Assessing what is easily measured	Assessing what is most highly valued

In addition to a pedagogical basis in sound educational principles, the content of curriculum must be age-appropriate and consistent with state and national standards. For chemistry, the National Science Education Standards (NSES) (NRC, 1996) outline chemistry concepts appropriate for each grade band (grades K-4, 5-8, and 9-12) within the physical science content standards. The NSES standards for physical science are given as Appendix 7.2. We also include the NSES inquiry standards as Appendix 7.3. These designate the "abilities and understandings" of inquiry that indicate what children should be able to do in designing and carrying out an investigation, and what they should understand about the nature of science. Smith et al. (2006) offer a research-based learning progression for concepts about matter and atomic-molecular theory that is a helpful guide to sequencing the development of key chemical concepts for children in grades K-8, even before they take a designated chemistry course. The matrix of "big ideas" offered by these authors (Smith et al., 2006, pp. 14-16) is included as Appendix 7.4. The appendices are offered as potential assistance to future reviewers in judging the age-appropriateness of chemistry concepts proposed as topics for K-12 school or outreach programs.

4.4.1 Elementary and Middle School Curriculum

Since Kesidou and Roseman's (2002) review, which covered 1995-1998 curriculum editions, a number of existing curriculum resources have been developed that offer the types of educational experiences in chemistry that appear to be consistent with the research evidence. Several kit-based programs for elementary and middle schools have been funded on a large scale by the National Science Foundation and others. These include FOSS (Full Option Science System), STC (Science and Technology for Children), and BSCS Science Tracks. All offer multi-week, in-depth, curricula that are based on investigation with real materials, supported by classroom-ready kits, and centered around questions of student interest. The kits also incorporate many opportunities for mathematics and literacy development through calculating, graphing, reading and writing activities that are intrinsic to the content investigations. Evaluation of the kits shows them to enhance student learning, especially when supported by teacher professional development and by school- or district-based support for distributing and refurbishing the kits. Many of the kits incorporate chemistry content at the upper elementary and middle school (MS) levels. To illustrate typical chemistry-related content of the kits, we list several examples from the NSF-funded programs; quotations are taken from publishers' materials.

- FOSS Mixtures & Solutions (grades 3-6): "Welcome to the Mixtures and Solutions Module, where you learn basic concepts of chemistry! You can take a trip to the junkyard to find out what elements are in the materials we discard." http://www.fossweb.com/modules3-6/index.html
- FOSS Weather and Water (MS): "Discover how understanding weather is more than reading a thermometer and recording air-pressure measurements. What do atoms and molecules, changes of state, and heat transfer have to do with weather?" http://www.fossweb.com/modulesMS/index.html
- STC Food Chemistry (grades 4-6): "Students explore basic concepts related to food and nutrition. They set up their own classroom laboratory and perform physical and chemical tests to identify the presence of starch, glucose, fats, and proteins in common foods. …In a final challenge, students apply their knowledge and skills to analyze the nutritional components of a marshmallow." http://www.carolina.com/carolina_curriculum/stc/units/food.asp
- BSCS Tracks Investigating Changing Properties (grade 4): "Students observe the properties of five household substances—alum, salt, cornstarch, baking soda and talcum powder—and investigate changes in the properties of those substances as they react with water, vinegar, red cabbage juice and iodine. Because students often think of chemical reactions as "magic," this module helps students build an understanding that chemicals undergo predictable changes that can be controlled." http://www.bscs.org/curriculumdevelopment/elementary/tracks/overview.html

Other kits touch on chemistry-related topics such as solar energy, light, floating and sinking, and pollution.

In addition to the NSF-funded kit-based programs, some well-developed “add-on” programs with significant chemical content are available. The best-known of these are GEMS (Great Explorations in Math and Science) from the Lawrence Hall of Science, which offer well-tested, chemistry-related, curriculum supplements on topics such as chemical reactions, bubbles, crime lab chemistry, states of matter, solutions, pH, and secret formulas. Many of these offer student-engaging explorations that address fundamental chemical concepts; GEMS guides can be used more easily by teachers whose schools do not support kit-based programs. The GEMS guides have been extensively evaluated. More recent guides offer better support for teachers than earlier versions.

In sum, these examples illustrate that, for upper elementary and middle school grades, lack of high-quality chemistry education does *not* appear to be primarily due to the lack of availability of research-based curriculum. Rather, the curricular issues are ones of implementation and support: school and district adoption of strong science curricula; effective alignment of curriculum across grades, at the district level; and practical and intellectual support of these curricula in schools, addressing issues such as kit distribution and refurbishment, and professional development to enable teachers to understand and implement the content and pedagogy of the kits.

4.4.2 High School Curriculum

At the high school level, the curriculum situation is somewhat different. We have already reviewed concerns about high school chemistry curricula and teaching approaches. Research-based curricula for high school chemistry have been slower to develop, but several are now available. Like the middle school curricula, they incorporate inquiry approaches to teaching and learning, and use real-world problems to engage students in chemical concepts and their relevance to everyday life. BSCS has outlined these NSF-supported curricula in its *Profiles* publication. Quotations below reflect publisher-provided material, as summarized in *Profiles* (BSCS, 2007); further information on these materials is available at the *Profiles* web site.

- *Living By Chemistry*, developed by Angelica Stacy at UC Berkeley and the Lawrence Hall of Science, and published by Key Curriculum Press. This one-year general chemistry curriculum is designed to “encourage more students with diverse learning styles to learn real chemistry” and to “close the gap between low- and high-achieving students.” These claims are supported by evaluation data showing students’ pre-post gains on a challenging assessment (Claesgens et al., 2003). “*Living By Chemistry* integrates core chemistry content, process skills, and embedded assessments in meaningful contexts. Student-centered and teacher-facilitated, the curriculum introduces students to the ways chemists think about the world and approach some of the complex problems that face today’s society.” The five modular units—Alchemy, Smells, Weather, Toxins, and Fire—each consist of a series of real-world investigations and together cover a full year of high school chemistry.
- *Active Chemistry*, developed by the American Institute of Chemical Engineers and Arthur Eisenkraft, and published by It's About Time/Herff Jones. This modular, inquiry-based chemistry course introduces students to chemistry concepts on a need-to-know basis as they explore chapters like “Movie Special Effects”, “The Periodic Table”, and “Cool Chemistry Show”. “Active Chemistry meets both national and state requirements and engages students of all learning levels. The curriculum was developed using an instructional strategy that

combines guided inquiry and whole class instruction with appropriate content." This enables students of all learning levels—special education to honors courses—to embrace fundamental concepts of chemistry.

- *ChemDiscovery*, developed at the University of Northern Colorado and published by Kendall/Hunt. "*ChemDiscovery* introduces a design approach to teaching chemistry, through a series of projects called quests that assist students in designing a virtual picture of the world from a chemical perspective. Each quest has overlapping content and context that offer the opportunity to learn chemistry content directly and/or contextually. The quests involve students in designing chemical structures and large, complex systems, and invite students to enter the world of chemistry from one of two perspectives: Design of the Universe (exploration of the origin and structure of the universe) or Living in the Universe (environmental impact). The program is centered on a CD-ROM that allows students to construct individual pathways through the learning environment. Teachers work as facilitators and collaborators to guide student learning. The *ChemDiscovery* CD-ROM contains activities, resources, databases, chemical calculation tools, a design studio, virtual experiments and field trips, and an electronic journal."
- *Chemistry in the Community* (ChemCom). Developed by the American Chemical Society and published by W.H. Freeman. "The *ChemCom* textbook is organized around themes that use a societal issue with chemistry applications, and is designed to offer a wide range of college-bound students an engaging approach to the study of chemistry. The material emphasizes problem-solving techniques and critical-thinking skills to facilitate decision-making about scientific and technological issues. Laboratory, decision-making, and problem-solving activities are an integral part of each unit and require student participation and cooperation for success. *ChemCom* introduces considerably more content from organic, nuclear, industrial, and biochemistry than most conventional chemistry courses." The textbook is organized into seven units: four to be taught sequentially (Water, Materials, Petroleum, Air) and three elective units (Industry, Atoms, Food).

These materials are largely targeted to first-year high school chemistry courses. No inquiry-based curriculum for AP or IB chemistry courses were reviewed in the 2007 edition of *BSCS Profiles*. However, as discussed, designation of chemistry courses as AP or IB courses does not guarantee their quality. The NRC report (Stanitski, 2002) argues that other types of advanced courses in high school may serve students better than the exam-driven, coverage-heavy and investigation-poor approach that they find is typical among such courses. Good models of investigative curriculum for advanced high school courses may be a lacuna among current high school curriculum. The audience for these is also smaller but might be considered an important one, as these courses target high school students pursuing advanced chemistry studies.

To summarize, as for middle and upper elementary grades, high-quality chemistry instructional materials are available at the high school level. Indeed, the representation of chemistry materials has increased substantially in the 2007 edition of *BSCS Profiles* as compared with the 2002 edition. Several physical science programs with substantial chemistry content are also listed there. Thus the challenges for high school chemistry curricula include encouraging schools to adopt these programs; helping teachers to implement the student-active teaching and learning approaches that are embedded in them; and supporting these programs with appropriate laboratory equipment and professional development experiences. We thus make the following propositions about secondary chemistry curriculum for the Foundation's consideration:

- Curriculum development is not a local project. Both broad expertise and substantial resources are required to develop excellent instructional materials, test them widely, and revise them for wide use across the range of US schools. Locally developed curricula are rarely of high enough quality to ensure student learning, nor sufficiently adaptable or well-supported to lead to broad dissemination and use.
- At the middle school level, a number of well-tested curricula are available that incorporate substantial chemistry and appear to be consistent with research on learning. High-leverage strategies for improvement of middle school chemistry instruction include adoption, implementation, and support of existing, developmentally appropriate, research-based curricula.
- At the high school level, there have been greater gaps in curriculum. Increasingly, these gaps are being filled by projects that are led by chemists and that are developing investigative, real-world-relevant curricula for high school. Thus high-leverage strategies for improving high school curriculum include: promotion of investigative approaches and good assessment practices; support of teacher professional development to effectively use these; and collaborative efforts among teachers to improve teaching practices, adopt strong curricula, and align curricula with middle school and other high school science courses.
- Good curriculum is necessary but not sufficient for good chemistry instruction. The quality of any curriculum—even an excellent one—is subject to the quality of its implementation by teachers. Teacher professional development is addressed in a separate section below.

4.5 What Makes Chemistry Hard?

Another body of education research examines specific aspects of chemistry that differ from other areas of science. These aspects may explain in part what makes chemistry "hard" for students. Johnstone (1991) has argued that understanding chemistry involves working at three levels: macroscopic (phenomena that are open to the senses); sub-microscopic (the atomic/molecular level); and symbolic (the use of chemical and algebraic equations to represent or describe a phenomenon). A professional chemist understands "sodium" on these multiple levels simultaneously: a shiny, reactive metal, an atom with a single electron outside a series of filled electron shells, and the symbol Na—but many students do not.

Gabel (1999) points out that classroom instruction takes place mostly on the abstract and symbolic level, thus students fail to connect macroscopic and microscopic ideas to their symbolic representation. For example, most young children have scientifically incorrect but self-consistent views of the structure of matter (Nakhleh & Samarapungavan, 1999). Middle school students—who are more likely than younger children to have been taught about states of matter—have more knowledge of particulate matter but also offer less logical explanations of processes such as ice melting that are not consistent with their statements about particulate matter (Nahkleh, Samarapungavan & Saglam, 2005). The authors interpret this contradiction as showing that students have difficulty integrating their prior knowledge from everyday experience with macroscopic amounts of melting ice, with school-based microscopic explanations involving intermolecular interactions. Such confusion is particularly likely if classroom explanations fail to directly confront students' previously developed conceptions.

Useful reviews of misconceptions in chemistry include those by Nakhleh (1992), Griffiths (1994), Garnett, Garnett and Hackling (1995), Horton (2004), and Kind (2004). We highlight a few examples here to illustrate the challenges of teaching chemical concepts. Much research on chemical misconceptions has focused on difficulties in interrelating Johnstone's three levels — macroscopic, microscopic, and symbolic—in understanding the particulate nature of matter (Nakhleh, 1992). For example, many otherwise well-educated adults will assert that the woody mass of a giant redwood tree comes from the water and nutrients that the tree draws from soil, instead of from the photosynthetic conversion of tons of gaseous CO_2 to solid sugars and starches (Harvard-Smithsonian, 1997). School teaching about photosynthesis often emphasizes solar energy conversion but neglects to show how this process also generates solid plant matter from gaseous CO_2.

Likewise, numerous studies show that students can balance chemical equations or compute stoichiometry results, although they cannot correctly complete related conceptual tasks, such as selecting a correct representation of a reaction from drawings of atoms and molecules "before" and "after" the reaction (Horton, 2004; Haláková & Prokša, 2007). Misconceptions about phase changes are also rooted in misunderstandings of the particulate nature of matter (Yezierski & Birk, 2006). Approaches to addressing these conceptual difficulties have focused on helping students develop more accurate mental images of particulate behavior, through strategies such as drawing diagrams (Bunce & Gabel, 2002) or analyzing animations (Yezierski & Birk, 2006), coupled with discussing, writing, and other strategies to help students actively confront misconceptions and build new concepts.

Another large body of misconceptions research addresses heat, temperature, and other thermochemical ideas (e.g., Jasien & Oberem, 2002). For example, the common notion that a cold can of soda can be insulated by wrapping it in aluminum foil is very persistent, even among chemical experts (Lewis & Linn, 1994). Many students can cite textbook definitions of exothermic and endothermic reactions but cannot correctly identify a bond-breaking process (e.g. dissociation of Cl_2) as endothermic (Teichert & Stacy, 2002). The notion that bonds release energy when they are broken is very durable and may be fostered by instruction that fails to connect, for example, biology books' statements about ATP as an "energy-rich molecule" with chemists' language of bond-breaking and bond-forming. A dramatic educational experiment at UC Berkeley showed that a series of lectures that were well-organized and well-delivered, but that failed to confront this student misconception, led to significant *reduction* of students' scores on simple thermochemical problems used in pre/post testing. However, student scores improved when they participated in a one-hour guided inquiry experience that led students to directly confront the misconception and explore it through counter-examples (Teichert & Stacy, 2002).

Other studies have examined 3-D visualization as a specific skill required in chemistry, especially organic chemistry (Pribyl & Bodner, 1987; Carter, LaRussa, & Bodner, 1987). Independent tests of spatial skills correlate with student success not only on questions that involve explicit spatial tasks in chemistry (e.g. mentally rotating a two-dimensional representation of a molecule) but also more general problem-solving tasks that go beyond rote memory and routine application of an algorithm.

In sum, in addition to general principles of high-quality, inquiry-based science education, the education research base highlights several aspects of learning that are particular to chemistry. High-leverage strategies for secondary chemistry education might target these concepts and skills that are difficult for students and thus challenging for teachers, and thus which might benefit from particular attention. Such strategies would highlight approaches that:

- Emphasize conceptual understanding to serve as a foundation, not substitute, for computational reasoning;
- Include "real-world" problems that engage students, not merely as examples but as driving questions;
- Use technology in appropriate ways, not for "drill and kill"—rote practice at routine problems—but for tasks that are specifically enhanced by using technology, or that are otherwise impossible, such as visualization in multiple dimensions, animation of dynamic processes, exploration of large data sets, and so on;
- Address concepts or skills that are particularly significant for learning chemistry and draw upon the existing research base about overcoming these challenges.

4.6 The Special Place of Laboratory Work

Laboratory work is a traditional and valued aspect of chemistry instruction, but one that poses both a challenge and an opportunity for chemistry students and teachers (Nakhleh, Polles & Malina, 2003). Nearly four decades ago, Charen (1970) wrote:

> Traditionally, science curricula in the high schools of our nation have not been directed toward the development of the ability to do critical thinking (problem-solving). Even the laboratory, admirably suited to such development, has not been exploited, its natural assets being wasted while being generally loaded with 'kitchen-type' laboratory exercises without real significance.

A recent NRC report on laboratory instruction in high school science courses (Singer, Hilton & Schweingruber, 2004) offers a picture that is not much improved. Singer and colleagues find that the amount and quality of high school science lab work is on the wane for a variety of reasons: safety, budget and lawsuit concerns; over-emphasis on test preparation; the need for teacher preparation in the discipline so that they have the skills, knowledge, and confidence to teach labs; and old-school views of laboratory pedagogy (Washam, 2007). In their review of the research literature on laboratory work in science, Hofstein and Lunetta (2004) note that faith that lab work teaches "something important" is widespread among teachers, despite significant gaps in the research literature to support this belief. These authors recognize barriers to high-quality lab experiences in schools similar to those identified by Singer and coauthors, but they nonetheless conclude that:

- School laboratory activities have special potential as media for learning that can promote important science learning outcomes for students;
- Teachers need knowledge, skills, and resources that enable them to teach effectively in practical learning environments. Teachers need to be capable of enabling students to interact intellectually and physically, through hands-on investigation and minds-on reflection;
- Students' perceptions and behaviors in the science laboratory are greatly influenced by teachers' expectations and assessment practices and by the orientation of the associated laboratory guide, worksheets, and electronic media; and

- Teachers need ways to find out what their students are thinking and learning in the science laboratory and classroom.

For these reasons, improving chemistry laboratory work may be another potential target with high leverage for the Foundation.

Evidence for the effectiveness of laboratory work in fostering student learning in chemistry, specifically, is incomplete but encouraging. Among chemistry-specific studies of laboratory work, Domin (1999) offers a typology of chemistry laboratory instructional approaches. These are distinguished by the degree of open-endedness of the lab problems and whether the goals of lab work focus on content learning, scientific investigation, or both. He notes that many questions about the effectiveness of lab work for student learning are not yet well understood, particularly how various instructional approaches affect a wide range of student outcomes, including conceptual understanding, retention of knowledge, scientific reasoning skills, higher-order cognition, procedural skills, attitudes, and understanding of the nature of science.

Based on an extensive meta-analysis of literature on laboratory-based instruction for grades 7-14, Hilosky, Sutman and Schmuckler (2002) found that inquiry-based laboratory practices did result in enhanced content learning. Monteyne and Cracolice (2004) cite some additional examples of research showing benefits from inquiry labs, which they define as a "data-to-concepts approach where students are expected to identify and explain the pattern in the data collected," but also point out the low uptake of inquiry-based instructional approaches. Phelps and Lee (2003) find that pre-service high school chemistry teachers believe lab work is important but are not well-equipped to lead it. In their review, Nakhleh, Polles and Malina (2003) find that, while many aspects of laboratory-based learning are not well understood, the role of lab work in fostering understanding, problem-solving skills, and improving attitudes is potentially significant and worth further development. Hilosky, Sutman and Schmuckler (1998) make several recommendations to improve laboratory instruction:

- Reduce the number of investigations per course;
- Provide flexibility in the use of laboratory space and materials for student use;
- Use laboratory experiences to drive classroom instruction;
- Help instructors learn to serve as facilitators who assist students in developing their own plans or finding appropriate procedures for analyzing laboratory evidence;
- Redesign assessment to include assessment of learning from laboratory-based experiences;
- Recognize that designing laboratory experiences around newer chemistry content, in itself, does not insure that the approach to instruction is effective.

In sum, laboratory work is an important aspect of learning chemistry that appears to assist a variety of content, cognitive, and affective gains, but that is increasingly neglected in US schools. Based on these findings, we suggest the following propositions as guidance for future efforts in improving high school laboratory instruction:

- Effective laboratory pedagogy includes an emphasis on developing concepts and interpreting evidence, rather than following procedures and verifying concepts.
- Lab work should drive classroom content, not the reverse.

- Chemistry teachers would benefit from professional development in laboratory pedagogy, supporting student investigations, and assessment of student learning from lab work;
- Schools face practical and logistical challenges in supporting high-quality lab work. Safety, chemical storage, scheduling, and teacher support should be addressed by any instructional reforms proposed for lab work.

4.7 Teacher Professional Development

Development of an effective teaching workforce is crucial to the success of school chemistry education. Darling-Hammond (1999) has summarized the evidence showing that, in general, teacher quality correlates with student learning. Teacher quality depends on a combination of factors: experience, general academic preparation, teacher education and certification, and ongoing professional development. Unfortunately, teacher quality is not equitably distributed across American schools. Schools in communities with high socioeconomic status (SES) are also likely to attract better prepared, more experienced teachers, while low-SES communities tend to have a higher proportion of less well-prepared and less experienced teachers.

Many teachers in charge of chemistry courses have less academic background in chemistry than desirable. While most high school teachers do have a science degree, it may be a general science degree: More than half of teachers teaching physical science classes (here including chemistry, physics, Earth science, or space science) do not have an academic major or minor in *any* of the physical sciences (NRC, 2000, pp. 50-51). Roehrig and Luft (2004) conclude that lack of preparation in the discipline is a significant barrier to teachers' ability and willingness to implement inquiry-based chemistry lessons—thus content knowledge is a necessary, but not sufficient, prerequisite to using more effective teaching and learning strategies.

In this review, we do not address teacher preparation (also called teacher education) programs, although there is much literature on this subject. However, we note that the leverage points on pre-service teacher education differ from those on in-service education. Teacher preparation and certification are controlled by states through licensing of higher education institutions to certify teachers, whereas teacher professional development for in-service teachers is offered by schools, museums, colleges, and professional groups. Improvement of teacher preparation is strongly connected to improvement of undergraduate science teaching in general: If pre-service teachers experience traditional, coverage-intensive lecture courses, they will be inclined to teach science this way themselves and to believe that this is how science "should" be taught (Phelps & Lee, 2003). Gabel (2004) reviews the literature on teacher preparation, highlighting innovative approaches to improving chemistry education for pre-service elementary teachers.

Rather we focus on teacher professional development (TPD), which refers to the ongoing professional education of practicing teachers. TPD may include many formats: courses, workshops, practica, study groups, professional learning groups, coaching or mentoring, action research, evaluation of student work, lesson study, or online communities (see Loucks-Horsley et al., 2003, p. 113). TPD may be offered by school districts, universities, professional organizations, or informal education institutions and is targeted to practicing or "in-service" teachers who are already in the classroom. In-service teachers are distinguished from "pre-service" teachers, who are preparing to be classroom teachers but who are not yet employed.

Teacher professional development is viewed as a high-leverage educational change strategy by many providers and funders, because working with one middle or high school teacher reaches over a hundred students each year, and many more over time if teachers' classroom practices are permanently influenced. However, it is also an indirect one: a long chain of events must take place for TPD to influence student achievement. Teachers must first learn new content and skills through TPD, then apply them effectively in their classrooms. For classroom change to last, teachers' beliefs must also be altered so that they continue to apply the new practices (Guskey, 2002). Thus establishing the effectiveness of TPD is difficult: causal association of TPD with student learning can be established only after a change in teacher classroom behavior is documented and changes in student achievement are also measured. Only recently have we seen solid, comparative evidence on a large scale for the positive impact of TPD on classroom practice and then on student achievement (e.g. Banilower et al., 2006; Porter et al., 2003; Desimone et al., 2002).

Loucks-Horsley et al. (2003) have distilled from the literature the principles of professional development for K-12 science and mathematics teachers. In their summary (pp. 44-47), effective professional development:

1. *Is driven by a vision of effective teaching and learning.*

   The classroom vision is coherent and pervasive and shapes the goals, content, and presentation of TPD. It is grounded in research on how students learn, emphasizing that learners actively construct their own knowledge with the teacher's guidance.

2. *Helps teachers to develop knowledge of both their content area and of ways to teach it effectively, and to examine their practice.*

   Teachers need both strong content knowledge and "pedagogical content knowledge" (PCK), or knowledge of how to best teach particular content (Shulman, 1987). Pedagogical content knowledge is distinct from generic pedagogical knowledge about "teaching methods" because it includes understanding of how students learn particular ideas, where they struggle, and how best to help them learn. For a chemistry teacher, *content knowledge* might include understanding how Valence Shell Electron Pair Repulsion (VSEPR) theory is used to predict molecular shapes. She should know the rules and procedures for using VSEPR to predict molecular shapes, and she should also know that this simple model of electron pair repulsion is predictive but not necessarily "the way it really works." Her *pedagogical content knowledge* includes the understanding that visualizing 3-D shapes is a learned skill, the ability to design and use effective hands-on model-building experiences to help students visualize three-dimensional shapes, and strategies for explicitly relating 3-D shapes to chemists' conventions for representing molecular shapes on 2-D paper. The teacher might use her general *pedagogical knowledge* to decide how to organize students for group work or to adapt the lesson for high-achieving or special education students. Pedagogical content knowledge is thus a knowledge base that enables teachers to "teach specific topics effectively and flexibly" under a variety of influences (van Driel, Verloop & de Vos, 1998).

   Effective TPD for chemistry teachers will help them to develop both content knowledge and pedagogical content knowledge. The literature reviewed by van Driel, Verloop and de Vos (1998) indicates that strong content knowledge is a prerequisite to pedagogical content knowledge, which largely develops through teaching experience. These authors also report an empirical study of teachers' PCK development in teaching chemical equilibrium, concluding that this can be enhanced through approaches that include critical review of instructional materials, laboratory experiments, and the study of authentic student work.

Brooks et al. (2007) describe a web-based approach to developing high school chemistry teachers' pedagogical content knowledge, through automated testing and feedback. While the authors analyzed the pros and cons of this approach, they offer no evidence that the approach results in teacher learning or changes in practice—a failing they share with the evaluation of many other TPD efforts (Guskey, 2000). Guskey (2002) argues that student work is particularly important in persuading teachers to change their classroom practice, as teachers are convinced by seeing evidence of learning among their own students.

3. *Mirrors methods to be used by students and engages adult learners*

   Teachers should experience the same, research-based teaching and learning methods their students will experience. TPD experiences in science should start where the teachers are and build from there; provide time for in-depth investigation, collaboration, and reflection; and connect explicitly to teachers' other activities and professional development experiences. For chemistry, effective TPD will include laboratory work, data analysis, computer modeling, problem-solving, and other authentic activities of chemists and chemistry students. Proven, high-quality materials should engage the learner in reasoning about chemical evidence.

4. *Builds a learning community through collaboration with colleagues and other experts.*

   Through this community, teachers are encouraged and rewarded to improve their practices, take risks, learn and share together. Effective TPD projects will include collaborative work, interaction with content and pedagogical experts, and ongoing interaction of the participants over time.

5. *Develops teacher leadership.*

   Teachers are supported to take on leadership roles to support other teachers, foster change in their schools, and promote reform. This might include teaming with other teachers, presenting to other teachers, action research projects, and other strategies. Effective TPD projects will include teachers as partners in deepening and strengthening their work and will offer opportunities for further growth and leadership as teachers progress.

6. *Links to the system.*

   Professional development is integrated with district and school initiatives, local and state curriculum standards, frameworks, and assessments, and actively supported by key school personnel (principals, district science coordinators) and the community. Recent research emphasizes the importance of linkage of professional development to the systems in which teachers work. This aspect is often weak when workshops or courses are offered by organizations outside the schools—yet these organizations can also offer content expertise and resources that schools do not have. Effective TPD projects will thus be attentive to these systemic linkages and will reflect real partnerships in their organization and leadership.

7. *Draws on student learning data and is continuously evaluated and improved.*

   Student learning data is used to set priorities and shape TPD experiences, while evaluation data from the TPD itself is used to improve the experience for future cohorts and ensure a positive impact. Teachers may gather student learning data in their own classrooms, examine state or district assessment data, analyze student work, or observe student learning in a colleague's classroom. Effective evaluation of TPD experiences will examine not only teacher satisfaction with the experience but teacher learning and its impact on their classroom practice.

These principles, and the research in which they are grounded, highlight several dilemmas for practitioners who offer teacher professional development programs. First, achieving these goals is not easily accomplished in short, "one-off" workshops. Recent research shows that 80-120 hours of contact time are required before significant changes in classroom practice and classroom culture are observed (Supovitz & Turner, 2000; Banilower et al., 2006). However, one-day workshops are popular with teachers; more intensive formats do not always draw the full range of teachers whose classroom work would benefit. Indeed, most professional development programs are voluntary, populated by teachers who already score high on several quality indicators and who are more likely to change than non-volunteers (Bobrowsky, Marx & Fishman, 2001). Thus drawing a broad population of teachers into extended professional development opportunities that can have real impact is a challenge.

Another issue is measuring the impact of TPD programs. The impact occurs downstream— the programs are offered to teachers, but the desired impact is on student outcomes. A common weakness in the literature we reviewed on teacher professional development in chemistry is a lack of evaluation data to support the claims made for impact. The literature we found offered several models of teacher professional development, including advanced degree programs for high school teachers, summer institutes, school-year programs, and online courses (e.g. Bretz, 2002; Blasie & Palladino, 2005; Sarquis, 2001; Gammon et al., 1999), but little evidence of impact. Descriptive information is often published to encourage others to offer teacher professional development using similar models. However, the research base, especially recent large-scale studies, suggests that the form of professional development matters less than core features that include its duration, emphasis on content linked with pedagogical content knowledge, and attention to the school and state systems in which teachers work (Banilower et al., 2006; Porter et al., 2003; Garet et al., 2001).

In sum, despite some challenges, teacher professional development in chemistry is one high-leverage strategy for improvement of secondary chemistry education that the Foundation may wish to consider. Criteria to consider in encouraging and evaluating high-quality proposals on teacher professional development in chemistry include:

- A project rationale that is focused on student learning and grounded in the chemical education and teacher professional development literature;
- Emphasis on increasing teachers' content knowledge jointly with pedagogical content knowledge development and understanding of how students learn content;
- Evidence of meaningful connection to state and district systems: standards and assessments, use of student data, and linkage to school structures and goals;
- Teacher use and review of proven instructional materials, rather than teacher-developed new materials;
- Innovative approaches to solving typical professional development challenges, such as drawing teachers into longer-duration experiences; engaging experienced and novice teachers, average and high-end teachers; and partnering effectively with chemists and educators in industry, informal science, higher education, and K-12 systems.

4.8 Informal Science Education

Informal science education is a popular category for foundation support that reaches broad audiences—families and adults as well as school-age children. The potential audience is also large: museums and media programs, for example, may reach very high numbers of participants. Informal science education is commonly believed to raise awareness generate interest and enthusiasm, and increase appreciation for science, and the research base that does exist supports these claims (Falk, 2001; Falk & Dierking, 2000). While many educational approaches are lumped together under the term "informal science," "free-choice learning," or "out-of-school learning," they may share little else: museums, after-school and summer programs for youth, TV, radio and film, and public outreach efforts have varied approaches, audiences and goals. Reviewing the outcomes of the full scope of informal science education approaches is outside the scope of this review, because it is very broad and extends beyond the targeted age groups.

The reasons for this lack of a research base lie in the inherent difficulties of studying any experience that is by definition "informal": the goals of informal science from those of school science education are less well defined; such experiences have short duration and high variability; and challenges of methodology and expense (Crane et al., 1994; Laursen et al., 2007). These problems apply to many types of informal science education, such as museum exhibits. Thus we expect that the general conclusion would not differ notably: "what works" has not been well studied.

In sum, high-quality informal science education is likely to be effective for enhancing public interest and appreciation for chemistry. For more detailed discussion of informal education, we refer the reader to Falk (2001) and Falk and Dierking (2000). A forthcoming review by Dierking (2007) conducted for the National Science Foundation, reviews the evidence for impact of informal science education.

5 Conclusion

In this report, we have described findings (in Section 2) from a study to gather and synthesize information about the activities and outcomes of the grant programs of a sample of foundations that support efforts to improve K-12 chemistry education and increase student interest in chemistry. We have also supported this empirical study with a review, presented in Section 4, of selected portions of the educational research literature on secondary chemistry education. Though these two approaches to answering the research question, "What works in secondary chemistry education?" are disparate, the findings from each are in good agreement with each other. This is reassuring, but no accident: many foundations are drawing on the educational research literature to steer their activities toward high-need areas and high-impact approaches. In addition, many philanthropic organizations are working to gather better data about the impact of their own work. The case exemplars described in Section 3 highlight some interesting approaches to this problem.

Another sign of the dynamic state of science education philanthropy is the fact that we have received several inquiries about this project; there is high interest in this work from the chemistry education community. Several of the foundations we contacted have also expressed significant interest in the approach and the findings. We congratulate the Camille and Henry Dreyfus Foundation on its forward-thinking approach to this issue, and we thank you for the opportunity to pursue this interesting question.

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Appendix 7.1: Glossary of Selected Terms Used in Chemistry Education

Algorithmic problem: Problem that can be solved by applying rules more or less automatically, e.g. following a specific procedure to solve a stoichiometry problem, draw a Lewis structure, etc. (contrast with conceptual question).

Concept map: A learning activity that can also be used for assessing student learning. Students generate or are given a list of conceptual terms related to a topic and arrange them, using arrows to relate concepts and verbs to describe the relationships, in a way that best represents their understanding of a topic (Nash, Liotta, & Bravaco, 2000).

Conceptual question: Question that taps a student's understanding of chemical ideas, requiring students to synthesize ideas rather than simply recall an answer or activate an algorithm. They may present a chemical situation that is new to the student and ask him to justify a choice, make a prediction, explain how or why something happens, link two ideas, recognize questions phrased in a novel way, or extract useful data from an excess of information (Nurrenbern & Robinson, 1998).

Content knowledge: Knowledge of scientific content in one's field, e.g. chemical concepts, facts and formulas, lab and problem-solving procedures specific to chemistry, etc. Compare with pedagogical content knowledge.

Discovery lab: Deductive lab approaches that emphasize discovering principles through data, rather than "proving" principles by matching data to prediction. Often used early in a learning sequence so that the resulting data is explored in subsequent classroom settings to derive general principles. Often based on collecting classroom sets of data –for example, students conduct the same reaction under different conditions and the class data set is used to discern trends or formulate general principles.

Formal education: Education within the school system. Compare with informal education.

Informal education: Education outside school systems, in e.g. museums, science centers, planetaria, zoos. May include after-school youth programs such as scouting, boys' and girls' clubs, etc. Some definitions include TV, radio, film and web media. Compare with formal education. Also called "out of school," "free-choice" or "lifelong" learning.

Inquiry: Teaching approaches that mirror scientific investigation: posing a question, gathering, evaluating and explaining evidence, considering alternate explanations. "Guided inquiry" approaches walk students through this process in some stepwise fashion, while "open inquiry" approaches leave the investigative approach to students, to varying degrees that should be developmentally appropriate.

Learning community, professional learning community: Teacher professional development strategy that develops and supports in-person or electronic networks of teachers to explore and discuss topics of interest, set and pursue shared goals, share information and strategies, and identify and address common problems (Bybee, 2002, p. 20).

Lesson study: A teacher professional development method borrowed from Japanese schools, in which teachers work in collaborative teams to design a "research lesson," observe student response when it is implemented in the classsroom, and refine the lesson based on their observations. At this time, most of the research base on lesson study is from mathematics teaching but it is being adapted successfully to science teacher professional development.

Metacognition: Knowledge of one's own cognitive processes; thinking about one's own thinking. It may include knowledge about thinking (e.g. knowing what factors affect the ability to memorize something), awareness of one's own thought (e.g. monitoring one's understanding while reading), ability to regulate one's thinking (e.g. making a choice to re-read a difficult passage), and readiness or willingness to apply this ability to regulate one's own thinking in practice (Rickey & Stacy, 2000).

Pedagogical content knowledge: Knowledge of how students learn the content and how to teach it to students, such as recognizing student difficulties or misconceptions; listening to students' ideas and posing questions that help them recognize and revise misconceptions; identifying teaching or assessment strategies that are effective for particular topics; finding real-world examples to engage students; and so on.

Standards: List of knowledge, skills and understandings that a student should gain in school. The National Science Education Standards were established as a project of the National Research Council; they are voluntary but, with the AAAS Benchmarks for Science Literacy, have served as models for many states. Most states have identified their own standards and use these to set assessments and proficiency levels for state testing under the No Child Left Behind laws.

Verification lab: Lab experiment that emphasizes verifying a chemical law or equation. Often emphasizes following a procedure correctly to achieve a correct result (e.g. graded based on error from a standard value). Thus also called "cookbook" lab.

Appendix 7.2 National Science Education Standards for Physical Science

Adapted from NRC (1996), Ch. 6, http://www.nap.edu/readingroom/books/nses/

TABLE 6.2. PHYSICAL SCIENCE STANDARDS

LEVELS K-4	LEVELS 5-8	LEVELS 9-12
Properties of objects and materials	Properties and changes of properties in matter	Structure of atoms
Position and motion of objects	Motions and forces	Structure and properties of matter
Light, heat, electricity, and magnetism	Transfer of energy	Chemical reactions
		Motions and forces
		Conservation of energy and increase in disorder
		Interactions of energy and matter

<u>Guide to the Physical Science Content Standard: K-4</u>

Fundamental concepts and principles that underlie this standard include

PROPERTIES OF OBJECTS AND MATERIALS

- Objects have many observable properties, including size, weight, shape, color, temperature, and the ability to react with other substances. Those properties can be measured using tools, such as rulers, balances, and thermometers.
- Objects are made of one or more materials, such as paper, wood, and metal. Objects can be described by the properties of the materials from which they are made, and those properties can be used to separate or sort a group of objects or materials.
- Materials can exist in different states--solid, liquid, and gas. Some common materials, such as water, can be changed from one state to another by heating or cooling.

POSITION AND MOTION OF OBJECTS

- The position of an object can be described by locating it relative to another object or the background.
- An object's motion can be described by tracing and measuring its position over time.
- The position and motion of objects can be changed by pushing or pulling. The size of the change is related to the strength of the push or pull.
- Sound is produced by vibrating objects. The pitch of the sound can be varied by changing the rate of vibration.

LIGHT, HEAT, ELECTRICITY, AND MAGNETISM

- Light travels in a straight line until it strikes an object. Light can be reflected by a mirror, refracted by a lens, or absorbed by the object.
- Heat can be produced in many ways, such as burning, rubbing, or mixing one substance with another. Heat can move from one object to another by conduction.
- Electricity in circuits can produce light, heat, sound, and magnetic effects. Electrical circuits require a complete loop through which an electrical current can pass.
- Magnets attract and repel each other and certain kinds of other materials.

<u>Guide to the Physical Science Content Standard: 5-8</u>

Fundamental concepts and principles that underlie this standard include

PROPERTIES AND CHANGES OF PROPERTIES IN MATTER

- A substance has characteristic properties, such as density, a boiling point, and solubility, all of which are independent of the amount of the sample. A mixture of substances often can be separated into the original substances using one or more of the characteristic properties.
- Substances react chemically in characteristic ways with other substances to form new substances (compounds) with different characteristic properties. In chemical reactions, the total mass is conserved. Substances often are placed in categories or groups if they react in similar ways; metals is an example of such a group.
- Chemical elements do not break down during normal laboratory reactions involving such treatments as heating, exposure to electric current, or reaction with acids. There are more than 100 known elements that combine in a multitude of ways to produce compounds, which account for the living and nonliving substances that we encounter.

MOTIONS AND FORCES

- The motion of an object can be described by its position, direction of motion, and speed. That motion can be measured and represented on a graph.[See Content Standard D (grades 5-8)]
- An object that is not being subjected to a force will continue to move at a constant speed and in a straight line.
- If more than one force acts on an object along a straight line, then the forces will reinforce or cancel one another, depending on their direction and magnitude. Unbalanced forces will cause changes in the speed or direction of an object's motion.

TRANSFER OF ENERGY

- Energy is a property of many substances and is associated with heat, light, electricity, mechanical motion, sound, nuclei, and the nature of a chemical. Energy is transferred in many ways.

- Heat moves in predictable ways, flowing from warmer objects to cooler ones, until both reach the same temperature.
- Light interacts with matter by transmission (including refraction), absorption, or scattering (including reflection). To see an object, light from that object--emitted by or scattered from it--must enter the eye.
- Electrical circuits provide a means of transferring electrical energy when heat, light, sound, and chemical changes are produced.
- In most chemical and nuclear reactions, energy is transferred into or out of a system. Heat, light, mechanical motion, or electricity might all be involved in such transfers.[See Unifying Concepts and Processes]
- The sun is a major source of energy for changes on the earth's surface. The sun loses energy by emitting light. A tiny fraction of that light reaches the earth, transferring energy from the sun to the earth. The sun's energy arrives as light with a range of wavelengths, consisting of visible light, infrared, and ultraviolet radiation.

<u>Guide to the Physical Science Content Standard: 9-12</u>

Fundamental concepts and principles that underlie this standard include

STRUCTURE OF ATOMS

- Matter is made of minute particles called atoms, and atoms are composed of even smaller components. These components have measurable properties, such as mass and electrical charge. Each atom has a positively charged nucleus surrounded by negatively charged electrons. The electric force between the nucleus and electrons holds the atom together.
- The atom's nucleus is composed of protons and neutrons, which are much more massive than electrons. When an element has atoms that differ in the number of neutrons, these atoms are called different isotopes of the element.
- The nuclear forces that hold the nucleus of an atom together, at nuclear distances, are usually stronger than the electric forces that would make it fly apart. Nuclear reactions convert a fraction of the mass of interacting particles into energy, and they can release much greater amounts of energy than atomic interactions. Fission is the splitting of a large nucleus into smaller pieces. Fusion is the joining of two nuclei at extremely high temperature and pressure, and is the process responsible for the energy of the sun and other stars.
- Radioactive isotopes are unstable and undergo spontaneous nuclear reactions, emitting particles and/or wavelike radiation. The decay of any one nucleus cannot be predicted, but a large group of identical nuclei decay at a predictable rate. This predictability can be used to estimate the age of materials that contain radioactive isotopes.

STRUCTURE AND PROPERTIES OF MATTER

- Atoms interact with one another by transferring or sharing electrons that are furthest from the nucleus. These outer electrons govern the chemical properties of the element.
- An element is composed of a single type of atom. When elements are listed in order according to the number of protons (called the atomic number), repeating patterns of physical and chemical properties identify families of elements with similar properties. This "Periodic Table" is a consequence of the repeating pattern of outermost electrons and their permitted energies.
- Bonds between atoms are created when electrons are paired up by being transferred or shared. A substance composed of a single kind of atom is called an element. The atoms may be bonded together into molecules or crystalline solids. A compound is formed when two or more kinds of atoms bind together chemically.
- The physical properties of compounds reflect the nature of the interactions among its molecules. These interactions are determined by the structure of the molecule, including the constituent atoms and the distances and angles between them.
- Solids, liquids, and gases differ in the distances and angles between molecules or atoms and therefore the energy that binds them together. In solids the structure is nearly rigid; in liquids molecules or atoms move around each other but do not move apart; and in gases molecules or atoms move almost independently of each other and are mostly far apart.
- Carbon atoms can bond to one another in chains, rings, and branching networks to form a variety of structures, including synthetic polymers, oils, and the large molecules essential to life.

CHEMICAL REACTIONS

- Chemical reactions occur all around us, for example in health care, cooking, cosmetics, and automobiles. Complex chemical reactions involving carbon-based molecules take place constantly in every cell in our bodies. [See Content Standard C (grades 9-12)]
- Chemical reactions may release or consume energy. Some reactions such as the burning of fossil fuels release large amounts of energy by losing heat and by emitting light. Light can initiate many chemical reactions such as photosynthesis and the evolution of urban smog.
- A large number of important reactions involve the transfer of either electrons (oxidation/reduction reactions) or hydrogen ions (acid/base reactions) between reacting ions, molecules, or atoms. In other reactions, chemical bonds are broken by heat or light to form very reactive radicals with electrons ready to form new bonds. Radical reactions control many processes such as the presence of ozone and greenhouse gases in the atmosphere, burning and processing of fossil fuels, the formation of polymers, and explosions.
- Chemical reactions can take place in time periods ranging from the few femtoseconds (10-15 seconds) required for an atom to move a fraction of a chemical bond distance to

geologic time scales of billions of years. Reaction rates depend on how often the reacting atoms and molecules encounter one another, on the temperature, and on the properties--including shape--of the reacting species.

- Catalysts, such as metal surfaces, accelerate chemical reactions. Chemical reactions in living systems are catalyzed by protein molecules called enzymes.

MOTIONS AND FORCES

- Objects change their motion only when a net force is applied. Laws of motion are used to calculate precisely the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated using the relationship $F = ma$, which is independent of the nature of the force. Whenever one object exerts force on another, a force equal in magnitude and opposite in direction is exerted on the first object.
- Gravitation is a universal force that each mass exerts on any other mass. The strength of the gravitational attractive force between two masses is proportional to the masses and inversely proportional to the square of the distance between them.
- The electric force is a universal force that exists between any two charged objects. Opposite charges attract while like charges repel. The strength of the force is proportional to the charges, and, as with gravitation, inversely proportional to the square of the distance between them.
- Between any two charged particles, electric force is vastly greater than the gravitational force. Most observable forces such as those exerted by a coiled spring or friction may be traced to electric forces acting between atoms and molecules.
- Electricity and magnetism are two aspects of a single electromagnetic force. Moving electric charges produce magnetic forces, and moving magnets produce electric forces. These effects help students to understand electric motors and generators.

CONSERVATION OF ENERGY AND THE INCREASE IN DISORDER

- The total energy of the universe is constant. Energy can be transferred by collisions in chemical and nuclear reactions, by light waves and other radiations, and in many other ways. However, it can never be destroyed. As these transfers occur, the matter involved becomes steadily less ordered. [See Content Standard C (grades 9-12)]
- All energy can be considered to be either kinetic energy, which is the energy of motion; potential energy, which depends on relative position; or energy contained by a field, such as electromagnetic waves.
- Heat consists of random motion and the vibrations of atoms, molecules, and ions. The higher the temperature, the greater the atomic or molecular motion.
- Everything tends to become less organized and less orderly over time. Thus, in all energy transfers, the overall effect is that the energy is spread out uniformly. Examples are the transfer of energy from hotter to cooler objects by conduction, radiation, or convection and the warming of our surroundings when we burn fuels.

INTERACTIONS OF ENERGY AND MATTER

- Waves, including sound and seismic waves, waves on water, and light waves, have energy and can transfer energy when they interact with matter. [See Content Standard D (grades 9-12)]
- Electromagnetic waves result when a charged object is accelerated or decelerated. Electromagnetic waves include radio waves (the longest wavelength), microwaves, infrared radiation (radiant heat), visible light, ultraviolet radiation, x-rays, and gamma rays. The energy of electromagnetic waves is carried in packets whose magnitude is inversely proportional to the wavelength.
- Each kind of atom or molecule can gain or lose energy only in particular discrete amounts and thus can absorb and emit light only at wavelengths corresponding to these amounts. These wavelengths can be used to identify the substance.
- In some materials, such as metals, electrons flow easily, whereas in insulating materials such as glass they can hardly flow at all. Semiconducting materials have intermediate behavior. At low temperatures some materials become superconductors and offer no resistance to the flow of electrons.

Appendix 7.3 National Science Education Standards for Science as Inquiry

Adapted from NRC (1996), Ch. 6, http://www.nap.edu/readingroom/books/nses/

TABLE 6.1. SCIENCE AS INQUIRY STANDARDS

LEVELS K-4	LEVELS 5-8	LEVELS 9-12
Abilities necessary to do scientific inquiry	Abilities necessary to do scientific inquiry	Abilities necessary to do scientific inquiry
Understanding about scientific inquiry	Understanding about scientific inquiry	Understanding about scientific inquiry

Guide to the Science as Inquiry Standard: K-4

Fundamental abilities and concepts that underlie this standard include

ABILITIES NECESSARY TO DO SCIENTIFIC INQUIRY

- ASK A QUESTION ABOUT OBJECTS, ORGANISMS, AND EVENTS IN THE ENVIRONMENT. This aspect of the standard emphasizes students asking questions that they can answer with scientific knowledge, combined with their own observations. Students should answer their questions by seeking information from reliable sources of scientific information and from their own observations and investigations.
- PLAN AND CONDUCT A SIMPLE INVESTIGATION. In the earliest years, investigations are largely based on systematic observations. As students develop, they may design and conduct simple experiments to answer questions. The idea of a fair test is possible for many students to consider by fourth grade.
- EMPLOY SIMPLE EQUIPMENT AND TOOLS TO GATHER DATA AND EXTEND THE SENSES. In early years, students develop simple skills, such as how to observe, measure, cut, connect, switch, turn on and off, pour, hold, tie, and hook. Beginning with simple instruments, students can use rulers to measure the length, height, and depth of objects and materials; thermometers to measure temperature; watches to measure time; beam balances and spring scales to measure weight and force; magnifiers to observe objects and organisms; and microscopes to observe the finer details of plants, animals, rocks, and other materials. Children also develop skills in the use of computers and calculators for conducting investigations.
- USE DATA TO CONSTRUCT A REASONABLE EXPLANATION. This aspect of the standard emphasizes the students' thinking as they use data to formulate explanations. Even at the earliest grade levels, students should learn what constitutes evidence and judge the merits or strength of the data and information that will be used to make explanations. After

students propose an explanation, they will appeal to the knowledge and evidence they obtained to support their explanations. Students should check their explanations against scientific knowledge, experiences, and observations of others.

- COMMUNICATE INVESTIGATIONS AND EXPLANATIONS. Students should begin developing the abilities to communicate, critique, and analyze their work and the work of other students. This communication might be spoken or drawn as well as written.[See Teaching Standard B]

UNDERSTANDINGS ABOUT SCIENTIFIC INQUIRY

- Scientific investigations involve asking and answering a question and comparing the answer with what scientists already know about the world.[See Content Standard G (grades K-4)]
- Scientists use different kinds of investigations depending on the questions they are trying to answer. Types of investigations include describing objects, events, and organisms; classifying them; and doing a fair test (experimenting).
- Simple instruments, such as magnifiers, thermometers, and rulers, provide more information than scientists obtain using only their senses.[See Program Standard C]
- Scientists develop explanations using observations (evidence) and what they already know about the world (scientific knowledge). Good explanations are based on evidence from investigations.
- Scientists make the results of their investigations public; they describe the investigations in ways that enable others to repeat the investigations.
- Scientists review and ask questions about the results of other scientists' work.

<u>Guide to the Science as Inquiry Content Standard: 5-8</u>

Fundamental abilities and concepts that underlie this standard include

ABILITIES NECESSARY TO DO SCIENTIFIC INQUIRY

- IDENTIFY QUESTIONS THAT CAN BE ANSWERED THROUGH SCIENTIFIC INVESTIGATIONS. Students should develop the ability to refine and refocus broad and ill-defined questions. An important aspect of this ability consists of students' ability to clarify questions and inquiries and direct them toward objects and phenomena that can be described, explained, or predicted by scientific investigations. Students should develop the ability to identify their questions with scientific ideas, concepts, and quantitative relationships that guide investigation.
- DESIGN AND CONDUCT A SCIENTIFIC INVESTIGATION. Students should develop general abilities, such as systematic observation, making accurate measurements, and identifying and controlling variables. They should also develop the ability to clarify their ideas that are influencing and guiding the inquiry, and to understand how those ideas compare with current scientific knowledge. Students can learn to formulate questions, design

investigations, execute investigations, interpret data, use evidence to generate explanations, propose alternative explanations, and critique explanations and procedures.

- USE APPROPRIATE TOOLS AND TECHNIQUES TO GATHER, ANALYZE, AND INTERPRET DATA. The use of tools and techniques, including mathematics, will be guided by the question asked and the investigations students design. The use of computers for the collection, summary, and display of evidence is part of this standard. Students should be able to access, gather, store, retrieve, and organize data, using hardware and software designed for these purposes.
- DEVELOP DESCRIPTIONS, EXPLANATIONS, PREDICTIONS, AND MODELS USING EVIDENCE. Students should base their explanation on what they observed, and as they develop cognitive skills, they should be able to differentiate explanation from description--providing causes for effects and establishing relationships based on evidence and logical argument. This standard requires a subject matter knowledge base so the students can effectively conduct investigations, because developing explanations establishes connections between the content of science and the contexts within which students develop new knowledge.
- THINK CRITICALLY AND LOGICALLY TO MAKE THE RELATIONSHIPS BETWEEN EVIDENCE AND EXPLANATIONS. Thinking critically about evidence includes deciding what evidence should be used and accounting for anomalous data. Specifically, students should be able to review data from a simple experiment, summarize the data, and form a logical argument about the cause-and-effect relationships in the experiment. Students should begin to state some explanations in terms of the relationship between two or more variables.
- RECOGNIZE AND ANALYZE ALTERNATIVE EXPLANATIONS AND PREDICTIONS. Students should develop the ability to listen to and respect the explanations proposed by other students. They should remain open to and acknowledge different ideas and explanations, be able to accept the skepticism of others, and consider alternative explanations.
- COMMUNICATE SCIENTIFIC PROCEDURES AND EXPLANATIONS. With practice, students should become competent at communicating experimental methods, following instructions, describing observations, summarizing the results of other groups, and telling other students about investigations and explanations.[See Teaching Standard B]
- USE MATHEMATICS IN ALL ASPECTS OF SCIENTIFIC INQUIRY. Mathematics is essential to asking and answering questions about the natural world. Mathematics can be used to ask questions; to gather, organize, and present data; and to structure convincing explanations.[See Program Standard C]

UNDERSTANDINGS ABOUT SCIENTIFIC INQUIRY

- Different kinds of questions suggest different kinds of scientific investigations. Some investigations involve observing and describing objects, organisms, or events; some involve collecting specimens; some involve experiments; some involve seeking more information;

some involve discovery of new objects and phenomena; and some involve making models.

- Current scientific knowledge and understanding guide scientific investigations. Different scientific domains employ different methods, core theories, and standards to advance scientific knowledge and understanding.
- Mathematics is important in all aspects of scientific inquiry.
- Technology used to gather data enhances accuracy and allows scientists to analyze and quantify results of investigations.
- Scientific explanations emphasize evidence, have logically consistent arguments, and use scientific principles, models, and theories. The scientific community accepts and uses such explanations until displaced by better scientific ones. When such displacement occurs, science advances.
- Science advances through legitimate skepticism. Asking questions and querying other scientists' explanations is part of scientific inquiry. Scientists evaluate the explanations proposed by other scientists by examining evidence, comparing evidence, identifying faulty reasoning, pointing out statements that go beyond the evidence, and suggesting alternative explanations for the same observations.
- Scientific investigations sometimes result in new ideas and phenomena for study, generate new methods or procedures for an investigation, or develop new technologies to improve the collection of data. All of these results can lead to new investigations.

Guide to the Science as Inquiry Content Standard: 9-12

Fundamental abilities and concepts that underlie this standard include

ABILITIES NECESSARY TO DO SCIENTIFIC INQUIRY

- IDENTIFY QUESTIONS AND CONCEPTS THAT GUIDE SCIENTIFIC INVESTIGATIONS. Students should formulate a testable hypothesis and demonstrate the logical connections between the scientific concepts guiding a hypothesis and the design of an experiment. They should demonstrate appropriate procedures, a knowledge base, and conceptual understanding of scientific investigations.
- DESIGN AND CONDUCT SCIENTIFIC INVESTIGATIONS. Designing and conducting a scientific investigation requires introduction to the major concepts in the area being investigated, proper equipment, safety precautions, assistance with methodological problems, recommendations for use of technologies, clarification of ideas that guide the inquiry, and scientific knowledge obtained from sources other than the actual investigation. The investigation may also require student clarification of the question, method, controls, and variables; student organization and display of data; student revision of methods and explanations; and a public presentation of the results with a critical response from peers. Regardless of the scientific investigation performed, students must use evidence, apply logic, and construct an argument for their proposed explanations.

- USE TECHNOLOGY AND MATHEMATICS TO IMPROVE INVESTIGATIONS AND COMMUNICATIONS. A variety of technologies, such as hand tools, measuring instruments, and calculators, should be an integral component of scientific investigations. The use of computers for the collection, analysis, and display of data is also a part of this standard. Mathematics plays an essential role in all aspects of an inquiry. For example, measurement is used for posing questions, formulas are used for developing explanations, and charts and graphs are used for communicating results.
- FORMULATE AND REVISE SCIENTIFIC EXPLANATIONS AND MODELS USING LOGIC AND EVIDENCE. Student inquiries should culminate in formulating an explanation or model. Models should be physical, conceptual, and mathematical. In the process of answering the questions, the students should engage in discussions and arguments that result in the revision of their explanations. These discussions should be based on scientific knowledge, the use of logic, and evidence from their investigation.
- RECOGNIZE AND ANALYZE ALTERNATIVE EXPLANATIONS AND MODELS. This aspect of the standard emphasizes the critical abilities of analyzing an argument by reviewing current scientific understanding, weighing the evidence, and examining the logic so as to decide which explanations and models are best. In other words, although there may be several plausible explanations, they do not all have equal weight. Students should be able to use scientific criteria to find the preferred explanations.
- COMMUNICATE AND DEFEND A SCIENTIFIC ARGUMENT. Students in school science programs should develop the abilities associated with accurate and effective communication. These include writing and following procedures, expressing concepts, reviewing information, summarizing data, using language appropriately, developing diagrams and charts, explaining statistical analysis, speaking clearly and logically, constructing a reasoned argument, and responding appropriately to critical comments. [See Teaching Standard B in Chapter 3]

UNDERSTANDINGS ABOUT SCIENTIFIC INQUIRY

- Scientists usually inquire about how physical, living, or designed systems function. Conceptual principles and knowledge guide scientific inquiries. Historical and current scientific knowledge influence the design and interpretation of investigations and the evaluation of proposed explanations made by other scientists. [See Unifying Concepts and Processes]
- Scientists conduct investigations for a wide variety of reasons. For example, they may wish to discover new aspects of the natural world, explain recently observed phenomena, or test the conclusions of prior investigations or the predictions of current theories.
- Scientists rely on technology to enhance the gathering and manipulation of data. New techniques and tools provide new evidence to guide inquiry and new methods to gather data, thereby contributing to the advance of science. The accuracy and precision of the data, and therefore the quality of the exploration, depends on the technology used. [Content Standard E (grades 9-12)]

- Mathematics is essential in scientific inquiry. Mathematical tools and models guide and improve the posing of questions, gathering data, constructing explanations and communicating results. [See Program Standard C]
- Scientific explanations must adhere to criteria such as: a proposed explanation must be logically consistent; it must abide by the rules of evidence; it must be open to questions and possible modification; and it must be based on historical and current scientific knowledge.
- Results of scientific inquiry—new knowledge and methods—emerge from different types of investigations and public communication among scientists. In communicating and defending the results of scientific inquiry, arguments must be logical and demonstrate connections between natural phenomena, investigations, and the historical body of scientific knowledge. In addition, the methods and procedures that scientists used to obtain evidence must be clearly reported to enhance opportunities for further investigation.

Appendix 7.4 Proposed Learning Progression for "Big Ideas" about Matter and Atomic-Molecular Theory for Grades K-8

Figure 1 from Smith et al., 2006, pp. 14-16.

Questions & Big Ideas	*Components of Big Ideas*	*K-2 Elaboration of Big Ideas*	*3-5 Elaboration of Big Ideas*	*6-8 Elaboration of Big Ideas*
1. What are things made of and how can we explain their properties? **1. Objects[1] are constituted of matter, which exists as many different material kinds. Objects have properties that can be measured and depend on amount of matter and on the material kinds they are made of.**	**Existence of matter and diversity of material kinds**	Objects are made of specific materials. There are different kinds of materials. The same kind of object can be made of different materials.	Objects are made of matter that takes up space and has weight. Solids, liquids, and air are forms of matter and share these general properties. There can be invisible pieces of matter (too small to see). There are many different kinds of materials.	Matter has mass, volume, and weight (in a gravitational field), and exists in three general phases, solids, liquids, and gas. Materials can be elements, compounds, or mixtures. **1AM. All matter is made of a limited number of different kinds of atoms, which are commonly bonded together in molecules and networks. Each atom takes up space, has mass, and is in constant motion.**
	Objects have properties that can be measured and explained. Three important properties are mass, weight, and volume.	Objects have certain properties--weight, length, area, and volume-- that can be described, compared and measured. (Only preliminary exploration and construction of volume measurement at this time.)	Weight is an additive property of objects that can be measured (e.g., the weight of an object is the sum of the weight of its parts). Volume is an additive property of an object that can be measured. The weight of an object is a function of its volume and the material it is made of.	Mass is a measure of amount of matter and is constant across location; weight is a force, proportional to mass and varies with gravitational field. Solids, liquids, & gases have different properties. **1AM. The mass and weight of an object is explained by the masses and weights of its atoms. The different motions & interactions of atoms in solids, liquids, and gases help explain their different properties.**
	Material kinds have characteristic properties that can be measured and explained.	The properties of materials can be described and classified. (Only readily observable properties, such as color, hardness, flexibility, are investigated at this time.)	Materials have characteristic properties that are independent of the size of the sample. (Extends knowledge to less obvious properties such as density, flammability, or conductivity at this time)	Materials have characteristic properties independent of size of sample (Extends knowledge to include boiling/freezing points and to elaborate on density) **1AM. The properties of materials are determined by the nature, arrangement and motion of the molecules that they are made of.**

[1] As mentioned in the text, we use the term object in the broad sense to refer to any bounded material entity, not just solids.

FIGURE 1 Overview of learning progression for matter and atomic-molecular theory.

Questions & Big Ideas	*Components of Big Ideas*	*K-2 Elaboration of Big Ideas*	*3-5 Elaboration of Big Ideas*	*6-8 Elaboration of Big Ideas*
2. What changes and what stays the same when things are transformed? **2. Matter can be transformed, but not created or destroyed, through physical and chemical processes**.	**Mass and weight are conserved across a broad range of transformations.**	There are some transformations (e.g., reshaping, breaking into pieces) where the amount of stuff and weight is conserved despite changes in perceptual appearance.	Matter continues to exist when broken into pieces too tiny to be visible. Amount of matter and weight are conserved across a broader range of transformations (e.g., melting, freezing, and dissolving.)	Mass and weight (but not volume) are conserved across chemical changes, dissolving, phase change & thermal expansion. **2AM: Mass and weight are conserved in physical and chemical changes because atoms are neither created nor destroyed.**
	Material kinds stay the same across some transformations and change across others.	Material kind stays the same when objects are reshaped or broken into small pieces. Freezing and melting changes some properties of materials but not others.	Materials can be changed from solid to liquid (and vice versa) by heating (or cooling) but are still the same kind of material. Combining two or more materials can produce a product with properties different from those of the initial materials.	Some transformations involve chemical change (e.g., burning, rusting) in which new substances, as indicated by their different properties, are created. In other changes (e.g., phase change, thermal expansion) materials may change appearance but the substances in them stay the same. **2AM: In chemical changes new substances are formed as atoms are rearranged into new molecules. The atoms themselves remain intact.** **2AM: In physical changes, molecules change arrangement and/or motion but remain intact, so the chemical substance remains the same.**

FIGURE 1 *(Continued)*

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3. How do we know? **3. We can learn about the world through measurement, modeling, and argument.**	**Good measurements provide more reliable and useful information about object properties than common sense impressions.**	Measurement involves comparison. Good measurements use iterations of a fixed unit (including fractional parts of that unit) to cover the measured space completely (no gaps). Measurements are more reliable than common sense impressions.	Although measurements are more reliable than common sense impressions, measurements can be more or less precise and there is always some measurement error. Instruments, such as microscopes, can extend our ability to observe and measure.	Our senses respond to combinations of physical properties, rather than isolated ones. For this reason, they are not good measures of those physical properties. Sources of measurement error can be examined and quantified. We can learn about the properties of things through indirect measurement (e.g., water displacement) as well as using powerful tools (microscopes). **3AM. Atoms are too small to see directly with commonly available tools.**
	Modeling is concerned with capturing key relations among ideas rather than surface appearance.	Some properties of objects can be analyzed as the sum of component units. (Students are involved with the implicit modeling of extensive quantities through the creation of measures).	Graphs, visual models, simple algebraic formulas or quantitative verbal statements can be used to represent inter-relations among variables and to make predictions about one variable from knowledge of others.	Models can propose unseen entities to explain a pattern of data. **3AM: The properties of and changes in atoms and molecules have to be distinguished from the macroscopic properties and phenomena for which they account.**
	Arguments use reasoning to connect ideas and data.	Ideas can be evaluated through observation and measurement.	Hypotheses and data are distinct. We make stronger arguments for our ideas when they fit a pattern of data rather than simply one observation. We can clarify our ideas by more precisely stating the conditions under which they are true.	Good arguments involve getting data that helps distinguish between competing explanations. **3AM. We learn about properties of atoms and molecules indirectly, using hypothetico-deductive reasoning.**

FIGURE 1 *(Continued)*