Society Committee on Education

Exploring the Molecular Vision

Conference Report
June 27-29, 2003

American Chemical Society

Organizing Committee

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The assistance of LaTrease Garrison, Cathy Nelson, Matt Thompson, and Michael Tinnesand is gratefully acknowledged.

About the Society Committee on Education

The Society Committee on Education (SOCED) ensures that American Chemical Society (ACS) educational activities focus on critical chemical education issues across all levels of instruction. SOCED periodically holds invitational conferences on issues of concern to the chemistry education community to help carry out its mandate. Participants in these conferences represent the highest levels of expertise on a given topic and help develop informed recommendations for possible approval by the Society's Board of Directors and implementation by SOCED. Previous SOCED conferences have led to the formulation of new policies and programs in chemical education within the ACS and have influenced the actions of individuals, other professional and scientific societies, government, and academic institutions. For more information, contact

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Summary

During his term as President of the American Chemical Society (ACS), Eli Pearce argued that the current presentation of chemical knowledge, which reflects the historical development of the subject in disciplinary silos, is becoming less useful as the frontiers of chemical research expand and become increasingly interdisciplinary (Pearce, 2002). He challenged the ACS Society Committee on Education (SOCED) to begin the task of "reinventing" the content of chemistry education at the undergraduate and graduate levels to better prepare students for success as future chemists.

SOCED organized an invitational conference, Exploring the Molecular Vision, in response to this challenge. The conference was designed to begin a discussion about the key concepts, factual knowledge, and skills that students need for today's chemistry careers.

The conference was held June 27-29, 2003. The 51 conference participants represented the chemistry community, other professional organizations, and federal government agencies. The first two keynote speakers, Jay Labov of the National Research Council (NRC) and Judith Ramaley of the National Science Foundation (NSF), addressed broad views of chemistry and education, thereby providing a context for all subsequent discussions. Labov helped conference participants realize that the challenges we face in chemistry are shared by other scientific disciplines. Ramaley reflected upon the broader implications for society and for chemistry of the trends toward interdisciplinary and integrative research. The third keynote speaker, Peter Atkins of Oxford University's Lincoln College, proposed reducing the content of chemistry education to an "irreducible minimum" for a broad spectrum of students.

Four panel presentations that made up the core of the conference agenda led to lively discussions among the participants in breakout sessions that followed each presentation. Participants first explored who uses chemistry and what educational experiences these practitioners need in order to have successful careers. They next asked what lessons could be learned from current chemistry education reform efforts. These discussions provided a context within which to explore how the frontiers and interfaces of modern chemistry research might redirect the curriculum. Finally, participants attempted to identify the essential skills and knowledge that future chemists need to be well prepared for today's workplace.

Who are the practitioners of chemistry, and what are their educational needs?

Practitioners of chemistry work -- and will continue to work -- in a wide range of environments. Chemists identify themselves and define their science on the basis of their ability to investigate the behavior of known materials at the molecular level, and to create entirely new materials. However, the skills, knowledge, and experiences that embody the practice of chemistry are changing as the boundaries blur between disciplines. Increasing numbers of scientists who do not think of themselves as chemists must use chemical knowledge in their daily work.

Employers want students to have a strong chemistry background that is complemented by other skills and knowledge that make them comfortable with multidisciplinary approaches, team-based work environments, and communicating their ideas clearly. Conference participants were very supportive of efforts to provide students with opportunities to solve real-world problems, to gain exposure to other disciplines, and have more research experiences to enhance chemistry education and meet these needs.

How is the content of chemistry education changing?

Most of the recent reform in chemistry education has focused on implementing new pedagogical approaches that reflect modern research on how students best learn chemistry, rather than redefining course content. The National Science Foundation has granted significant funding to modify curricula as well as to create and adopt content from other disciplines or successful curricular models. These efforts have so far had a limited impact. Hope was expressed that the influence of these projects will continue to grow in coming years. Breakout groups identified a number of areas where more concerted reform efforts are needed to improve content. These included efforts to introduce interdisciplinary courses, labs, and research opportunities; and to integrate discussion of the social impacts of chemistry and the individual responsibilities of chemists to make products and processes that are environmentally sustainable.

What are the new scientific frontiers and interfaces that impact upon chemistry?

Current frontier areas in chemistry and in other fields could impact the content of undergraduate and graduate level education. Of course, many important frontier areas that could have a great impact on future chemistry are not yet known. Conference participants benefited from a summary of grand challenges for chemistry and chemical engineering articulated in the NRC report, *Beyond the Molecular Frontier* (NRC, 2003a). Participants also discussed many nontechnical topics, ranging from ethics and environmental issues to the impact of globalization, to try to understand what forces might influence the knowledge base and the competencies and skills needed to conduct cutting-edge chemistry research. Frontier areas could be infused into courses or could be the focus of short supplementary lectures or external internships in industry or government laboratories to extend the fundamentals of chemistry. Faculty from other disciplines could be engaged in teaching general chemistry courses to enhance the content and relevance of the course.

What is the irreducible minimum of chemistry that students need to be effective chemists?

Participants used Atkins' presentation as a beginning point for breakout group discussions that focused on the essential knowledge of chemistry, and on other skills and experiences that students should acquire while studying for a chemistry degree.

Conference participants identified many fundamental chemical concepts and specific items of chemical information that are important to the practice of modern chemistry. Conference participants felt that chemistry education also needs to convey the nature of chemistry as an empirical science and the manner in which chemical scientists perform experiments, generate hypotheses, create models, and solve problems. All students should learn that chemists synthesize previously unknown elements, molecules, and materials, and systems made from these components. Most importantly, students should recognize chemistry is important because it contributes to the solution of societal problems.

Several conference participants noted that the undergraduate curriculum presents an unreasonably large collection of facts and concepts, especially given the recommended duration of study. Despite crowded curricula, time still needs to be found to portray the intellectual beauty, significance, and excitement of chemistry. To do this, conference participants thought that more emphasis is needed 1) on presenting the intellectual coherence and connections in the discipline; 2) on undergraduate research; 3) on the toxicity of chemicals and chemistry's role in supporting sustainable development; and 4) computational modeling and linkages to modern research technology. Ideally, students' experiences in university should prepare them for continuous learning throughout their careers. Recognizing the many audiences for chemistry education, desired outcomes need to be defined for a given audience before content can be specified.

Conclusions

Conference participants identified several gaps between the content of current chemistry education and the practice of the discipline. The content of chemistry education does not reflect the trend toward integration of all sciences. While an "irreducible minimum" content of chemistry could be identified for teaching purposes, any reforms based on this approach alone would not sufficiently reflect the current practice of chemistry. Chemistry education can only reflect the current practice of chemistry if it also includes: 1) the convergence of chemistry with other disciplines, particularly with biology and physics, 2) the impacts of improved mathematical and computational tools and of interactions through cyberspace, and 3) the relevance of the discipline through engagement with broader society and the promotion of high ethical standards and environmental performance.

Conference participants were in broad agreement on several issues related to the need for curriculum change and the future of the chemistry profession. Areas of agreement include:

Current curriculum

1. Existing programs are producing graduates with excellent training and qualifications who are able to secure employment in the chemical sciences.
2. Most of the conceptual and factual knowledge needed to prepare a practitioner of chemistry is included in current degree programs.
3. The content (i.e., facts, concepts, skills and experiences) of existing chemistry curricula is not always representative of the current practice of chemistry.

Educational reform efforts

4. In the process of education, the content of the chemistry curriculum cannot be divorced from the pedagogy employed in its instruction.
5. Past educational research and curriculum reform initiatives in chemistry have produced an important body of knowledge and instructional resources that should help to guide future curricular reform.
6. Although progress has been made, the number of college and university faculty participating in efforts to implement reform-based chemistry curricula must increase.

Participation in the profession

7. Content that demonstrates chemistry's relevance to society can help attract more diverse populations of students, faculty and researchers into the chemical sciences.

Preparation for the profession

8. Problem solving is one of the most empowering learning experiences for science students.
9. A deep knowledge of chemistry and the ability to pursue cutting-edge chemical research in teams have become even more central to innovation at the forefront of science and technology.
10. In addition to a strong background in chemistry, students should have many opportunities to master those skills that are essential for communicating across cultures, traditional roles, and disciplines.

11. Students need a wide range of experiences outside of science and technology to prepare them to be responsive to societal needs and concerns and to articulate the significance of the scientific enterprise to their fellow citizens.

Less agreement was evident on the importance of reforming the content of chemistry courses to address these issues. SOCED hopes that the Exploring the Molecular Vision conference marks the beginning of a productive discussion on how to ensure that what we teach students continues to attract talented students to the discipline, and that the education they receive prepares them for fulfilling careers in an ever-broadening range of employment.

SOCED does not recommend that the community undertake time intensive and transformational curriculum change without a clear understanding of well-defined needs. Recognizing that change has always taken place in education at an evolutionary pace, we nevertheless can set revolutionary goals for reinventing the content of chemistry education. Our efforts to meet these goals must be based on realistic analyses of need and expectations of what can be achieved. A future reform agenda should reflect the scientific, curricular, professional and social issues that are reshaping the nature of the chemical profession. The conclusions of the Exploring the Molecular Vision meeting challenge SOCED to collaborate with other stakeholders in the chemistry education community to thoroughly investigate these issues.

Introduction

Origin and Development of Exploring the Molecular Vision

During his term as President of the American Chemical Society (ACS), Eli Pearce argued that the current presentation of chemical knowledge reflects the historical development of the subject in disciplinary silos (Pearce, 2002). This approach is becoming less useful as the frontiers of chemical research expand and become increasingly interdisciplinary and as the practice of the discipline becomes increasingly team-oriented. Pearce asserted that, if chemistry education were started again from scratch, knowing what we know about the discipline today, its content would be organized and delivered very differently. He challenged the Society Committee on Education (SOCED) to begin the task of "reinventing" the content of chemistry courses at the undergraduate and graduate levels to better prepare students for success as future chemists.

In response to Pearce's challenge, SOCED organized an invitational conference, Exploring the Molecular Vision. The conference was designed to begin a discussion about the key concepts, factual knowledge, and skills that students need to be prepared for chemistry careers. One major difficulty in holding the conference was the short time available for a select group of busy scientists and engineers to make a significant contribution to the many complicated issues in chemistry education. The great breadth and multiple directions of chemistry education, the influence of modern research on teaching and learning, and the abundance of existing, high quality activity in the area of chemical education reform complicated the task. The conference organizing committee concluded that a reasonable probability of making a useful contribution to chemical education could be based on (1) bringing together a group that does NOT usually gather to discuss education but who, because of their activities (mostly research), collectively could provide a complete overview of the content and practice of the field of chemistry; (2) asking them to offer guidance on the content of chemistry for teaching purposes; and 3) providing a forum for chemistry educators and researchers to exchange ideas.

Conference participants

The conference organizing committee, consisting of 10 SOCED members, hosted 45 workshop participants, including speakers and panel members. Participants represented the entire chemistry community as well as other professional groups and government agencies concerned with science education. This distinguished group was comprised of many prominent scientists and educators, including a Nobel Laureate, members of the National Academy of Science, additional leaders from industrial, government, and academic laboratories, and many recent ACS presidents. Eighteen of the invited participants, panelists and speakers considered themselves to be chemical educators. The largest group of participants (~38%) represented Ph.D. granting universities. Another ~18% of the participants came from colleges and universities that focus on undergraduate education, ~7% from 2-year colleges, ~16% from government agencies concerned with education, and 13% from industries that hire chemists. The remaining 8% were from government laboratories and other professional societies and educational organizations. A complete list of participants is in Appendix B.

Initially, conference participants completed a brief survey to help the organizers understand how they viewed their own affiliations within the discipline of chemistry. When responses were grouped in terms of the classic fields of chemistry, about a third were organic chemists, a third were physical chemists, and the remainder was analytical, bio- or inorganic chemists. However, the survey responses indicated that the conference participants viewed themselves as representatives of a long list of subdisciplines, including those beginning with the "bio-" prefix; (e.g., bio-analytical). Participants variously identified themselves with chemical physics, and computational, macromolecular, materials, medicinal, pharmaceutical, theoretical, polymer, organometallic, and green chemistry.

The survey also asked participants to identify facts, skills, and concepts that they thought were important in the learning of chemistry. These appear in Appendix C. This list anticipated many of the discussions that were held during the conference and included:

- Many of the central concepts of chemistry;
- Other critical subjects such as ethics and environmental concerns;
- Other related issues such as team work and the trend toward interdisciplinarity in scientific fields;
- The relationship of pedagogy and content in the curriculum.

Conference agenda

The one-and-a-half day conference was planned around four key questions posed by the conference organizers and featured three keynote speakers and four panel discussions. Each panel discussion focused on one of the key questions and was followed by small group discussions. Each group reported back to the plenary before the next question was considered. The complete conference agenda is in Appendix D.

At the Friday evening session, Eli Pearce introduced the workshop and provided his vision for the conference. On Saturday morning, SOCED Chair Daryle Busch opened the conference with an overview of its purpose and agenda.

The general strategy was to begin with broad overviews of the many factors impacting upon efforts to "reinvent" chemistry education and progressively move discussion to focus on the content of chemistry education. Consequently, the first two keynote speakers, Jay Labov of the National Research Council (NRC) and Judith Ramaley of the National Science Foundation (NSF), addressed broad views of chemistry and education, thereby providing a context for all subsequent discussions. The third keynote speaker, Peter Atkins of Oxford University's Lincoln College, proposed reducing the content to be taught in chemistry education to an "irreducible minimum" for a broad spectrum of students.

The four panel presentations that made up the core of the conference agenda led to lively discussions among the participants in breakout sessions that followed each panel presentation. We first explored who does chemistry and what educational experiences these practitioners need in order to have successful careers. We next asked what lessons could be learned from current chemistry education reform efforts. These discussions provided a context within which to explore how the frontiers and interfaces of modern chemistry research might redirect the curriculum. Finally, we attempted to identify the essential skills and knowledge that future chemists need to be well prepared for today's workplace.

Summary of keynote addresses

Jay Labov is the Deputy Director of the NRC Center for Education and the Director of the Center's Division on Mathematics and Science Education. He addressed conference participants on Friday evening. Dr. Labov, trained as a biologist, is currently responsible for programs that cover all of science and math. Drawing on that broad base, he helped conference participants realize that the challenges we face in chemistry are shared with our neighbors in other scientific disciplines. He began his remarks by reminding conference participants that, "Education is what remains after one has forgotten everything he or she learned in school."

Dr. Labov used data from a survey of B.S. physicists that show what skills they believe are most important to success in their jobs. At the top of the list were scientific problem solving and the ability to synthesize information. Computer skills were rated higher than knowledge of physics. These findings presaged a general observation about science education. Dr. Labov anticipated that in the future, more emphasis would be placed on problem solving and on placing science in a broader context, and less emphasis on subject-matter content within the discipline. He foresaw a move toward integrating all aspects of science.

Three of the slides from this presentation are reproduced in Figures 1-3 to illustrate some of the challenge for the conference participants. The first slide demonstrated that a number of recommendations from a recent NRC report on advanced high school science courses (NRC, 2002) are equally applicable to the study of chemistry at the undergraduate and graduate level. The second slide reacts emotionally to the important, but daunting, task of seeking consensus on content, and the frustrating realization that this will always be a job unfinished. The third lists many of the important issues that cannot be readily separated from content. Indeed, content must be considered within a profoundly complex, multidimensional matrix, in order to proceed to educational practice

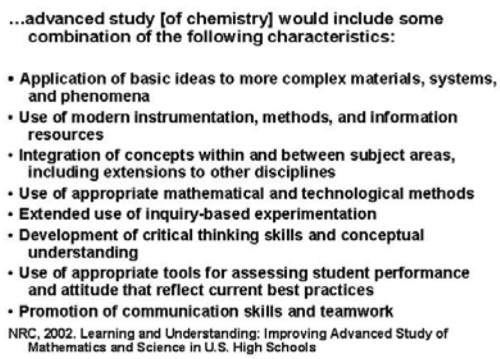

Figure 1

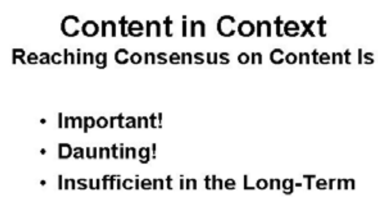

Figure 2

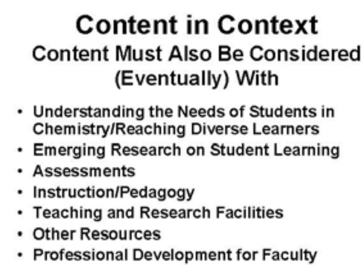

Figure 3

Judith Ramaley is Assistant Director for Education and Human Resources at the National Science Foundation (NSF). She addressed conference participants on Saturday morning. Speaking from her perspective as a biologist with enormous experience in education, Dr. Ramaley told conference participants that science has entered a new era. Disciplines are converging, drawn together by new mathematical and computational paradigms and interactions in cyberspace. Disciplines are further empowered by new tools that are emerging from areas such as nanoscience and genomics. Through interdisciplinary approaches, fields including biology and chemistry are transcending their traditional boundaries. The "New Biology," or the "New Chemistry," is as much about the integration of the disciplines and about how research is conducted as it is about any specific content. Her view was that, if a subject in chemistry or physics is important for understanding the New Biology, it should be integrated into the biology curriculum, rather than be studied in the context of the parent discipline.

Dr. Ramaley reflected upon the broader implications for society of the trends toward interdisciplinary and integrative research. She said that such research must be conducted in institutions that have improved the relevance of their curricula and made the curricula connect to the issues and problems faced by the broader society. An education in chemistry must become truly interdisciplinary and context based, while retaining the core features that define the discipline.

Going beyond engagement, Dr. Ramaley noted a new imperative for making ethics and civic responsibility part of the undergraduate experience. Drawing analogies to the recommendations of Gardner et al. (2002), she advocated that a baccalaureate graduate should be:

- Empowered through the mastery of intellectual and practical skills;
- Informed by knowledge about the natural and social worlds and the forms of inquiry basic to these studies; and
- Responsible for their personal actions and willing to work toward the public good.

Dr. Ramaley cited the NRC report, *Bio2010* (NRC, 2003b) as an excellent exploration of how the nature of scientific investigation is changing and how little of this remarkable shift is reflected in <u>what</u> undergraduates learn and <u>how</u> they learn. The report states, "we are not preparing our young people for careers in the New Biology, nor are we exposing other students to the wonders of this work and what it might mean for their own lives and their own professional pursuits." *Bio2010* concludes that the teaching of biology has been frozen in place for decades, in fair measure because instructors recognize that high school students may seek Advanced Placement credit and that many undergraduate biology students will take standardized entrance examinations for graduate and professional schools, especially if they are planning a career in medicine. Dr. Ramaley said that we should rethink the curriculum so that students experience the New Biology, or the New Chemistry, in ways that more accurately reflect the practice of the science, Standards and tests should then be redesigned to document what students have learned.

Returning to the implications of the New Chemistry, Dr. Ramaley noted that the classical fields like chemistry now transcend the boundaries of any individual discipline, as we have traditionally defined those boundaries. She encouraged conference participants to ask, "What kind of education can prepare students for careers in a field whose boundaries cease to have meaning?**"**

Dr. Ramaley envisioned a higher order of learning that prepares students for today's complex world. She described a content-rich, student-centered learning model that is based on the core assumption that students are more likely to learn if they play an active role in the process. "All of these elements must be kept in mind, lest a focus on content alone drive out our appreciation that any undergraduate education has larger goals than simply the transmission of knowledge," she said.

Peter Atkins is professor of chemistry at Oxford University, Lincoln College, and author of many textbooks, monographs and books about science. He addressed conference participants on Saturday evening. Dr. Atkins believes that there are two kinds of students, specialists and generalists. Potential specialists need to go beyond the acquisition of qualitative insight into the nature of matter and turn qualitative ideas into quantitative expressions. He shared his view that all of chemistry could be reduced to eight core ideas and related concepts and four types of chemical reactions:

1. Matter consists of atoms Stoichiometry, the prediction of amounts Key concept: mole ratio Secondary skill: quantitative prediction Key equation: $n = m/M$	2. Atomic structure The Schrödinger equation Key concept: wave-particle duality Secondary skill: cautious rationalization Key equation: $\lambda = h/p$	3. Atoms link by sharing electron pairs 4. Molecular shape is of paramount importance Localization *versus* delocalization Key concepts: VSEPR and molecular orbitals Secondary skill: intellectual flexibility Key equation: $V = e2/r$
5. There are residual forces between molecules The role of forces in cohesion Key concepts: kinetic energy *versus* potential energy Secondary skill: the constructive use of ignorance Key equations: $V = e^2/r$, $pV = 1/3nMc^2$	6. Energy is conserved The first law of thermodynamics Key concept: enthalpy as a state function Secondary skill: organization of information Key equation: $\Delta H = qp$	7. Energy and matter tend to spread The second law Key concepts: entropy and Gibbs energy Secondary skill: the network of nature Key equations: $\Delta G = -T\Delta S_{total}$, $\Delta G = -nFE$, $\Delta G° = -RT \ln K$

8. There are barriers to reaction	9. Four types of reaction
Activated processes and the role of temperature	Proton transfer, electron transfer, and electron sharing
Key concept: activation energy	Key concepts: pH, pK, and $E°$
Secondary skill: ?	Secondary skill: resolution of intricacy
Key equation: $k = A \exp(-E_a/RT)$	Key equation: $\Delta G = \Delta G° + RT \ln Q$

This reductionist approach outlines important basic principles that explain many patterns of chemical behavior. Dr. Atkins noted that the original purpose in developing these nine principles was to define a set of chemical concepts that every citizen should know. He did not suggest that this expression of chemistry content was sufficient knowledge for a professional chemist.

Much to the benefit of this conference, Atkins showed that one could indeed promote an irreducible minimum content of chemistry for teaching purposes. Subsequent discussion among conference participants explored other concepts that are equally important to the practice of modern chemistry (see Panel 4 breakout session report). Dr. Atkins' presentation demonstrated that an irreducible minimum alone could not be the sole basis for "reinventing" chemistry education so that it reflects the *current practice* of chemistry. The educational system can only reflect the *current practice* of chemistry if it also enhances the integrative convergence of chemistry with its boundary fields (e.g., biology, physics, engineering, geology), the impacts of amplified mathematical and computational tools and of interactions of scientists through cyberspace, the relevance to society at large required by engagement, and accompanying standards of ethics.

Who are the practitioners of chemistry and what are their educational needs?

Panelists: William H. Glaze, Professor in the Department of Environmental and Biomolecular Systems at Oregon Health & Science University; **Thomas J. Meyer,** Associate Director for Strategic Research at Los Alamos National Laboratory; **Elsa Reichmanis**, Bell Laboratories Fellow and Director of the Materials Research Department, and 2003 President, American Chemical Society

Facilitator: Morton Z. Hoffman, Boston University

Panel 1 and its attendant breakout sessions were given the charge to explore the following specific questions:

1-1. Where do the practitioners of chemistry work, and where will they work in the future?

1-2. To what extent do the practitioners of chemistry identify themselves as chemists? If they do not do so, why not?

1-3. What specific skills will employers want chemists and other practitioners of chemistry to have for successful careers in the future?

1-4. As we look to the future of chemistry, what is perceived to be missing from students' current education?

The term, "practitioners of chemistry," was chosen deliberately to cover all scientists who use chemistry in their jobs, not just those who actually consider themselves to be chemists. The first panelist, **Bill Glaze** emphasized the importance of chemistry in developing a full understanding on the molecular level of the complex systems that make up the environment. Chemistry has been essential in bringing environmental science to its present level of sophistication, and for changing the old paradigm of environmental protection from being *reactive* to more *proactive* in the prevention of waste and environmental deterioration. A molecular-level understanding of life, health, and environmental interactions will enable us to model the effects of chemicals on humans and other species with an unprecedented degree of certainty. Dr. Glaze urged those who plan the curriculum of the future to recognize that environmental science is an important field of applied chemistry and deserves to be an integral part of the course of study of future practitioners of chemistry.

Tom Meyer focused on the challenges of national and global security that chemistry will help to address: the relationship between energy resources and the condition of the environment, the use, of nuclear and other alternate power sources, the treatment and storage of nuclear waste, the possibilities of terrorist threats, and the prospects of emerging pathogens. He noted the distribution of U.S. energy sources: 70% fossil fuels (80-90% globally), 15% hydroelectric, 14% nuclear power, but only 1% renewable. Future practitioners of chemistry will contribute to the development of new technologies to sequester carbon dioxide; enhance the understanding of actinide chemistry and nuclear materials; and contribute new knowledge and technologies that facilitate the conversion to a hydrogen economy. Chemical scientists will develop new materials and detection devices to protect national security. Through their use of supercomputers, practitioners of chemistry will increase understanding of biological processes on the molecular level. Dr. Meyer stated that the practitioners of chemistry have a significant role to play in providing national security. He concluded by urging that the fundamentals of chemistry continue to be part of the curriculum, and not be thrown out for the sake of educational reform.

Elsa Reichmanis noted that chemistry practitioners work in many different environments: 62% in industry, 26% in academia, 7% in government, and 5% in other employment. In the future, it is likely that chemists, especially those in industry, will work in settings even more varied and less traditional than today because chemistry's future will be increasingly multidisciplinary and increasingly concerned with organized molecular systems. Even in nontraditional industries, a strong chemistry background will remain an asset for individuals. At the same time, skills in other disciplines, such as physics, computer science, mathematics, biology, and advanced materials development, will be critically important. Employers will want their chemists to have, in addition to a strong foundation in the subject, the training and flexibility to work well with others from other disciplines.

Panel 1 breakout group report

The breakout group discussions addressed the specific questions of the panel as well as issues raised by the panelists' presentations.

1-1. *Where do the practitioners of chemistry work, and where will they work in the future?*

Practitioners of chemistry work -- and will continue to work -- in a wide range of academic institutions, industrial and business establishments, and government laboratories and agencies. Looking ahead, practitioners of chemistry also will play important roles in evolving industries. Increasingly, chemists will have to work with, or as, biologists, physicists, engineers, material scientists, and other technical professionals. It will become increasingly rare for a working chemist to be surrounded by a majority of co-workers who are also chemists.

1-2. *To what extent do the practitioners of chemistry identify themselves as chemists? If they do not do so, why not?*

Chemists identify themselves and define their science on the basis of their ability to investigate the behavior of known materials at the molecular level, and to create entirely new materials. However, the skills, knowledge, and experiences that embody the practice of chemistry are changing as the boundaries blur between disciplines. Further, increasing numbers of scientists who do not think of themselves as chemists must use chemical knowledge in their daily work. Chemistry, the *central* science, has become the *enabling* science, making it possible for scientists to do stellar research in many disciplines. As a result, some of the more traditional chemists are finding it increasingly necessary to demonstrate the relevance of their work to current research goals. Higher education perpetuates a narrow definition of chemistry by continued emphasis on the traditional areas of chemistry. "ACS culture" (*i.e.*, approval and certification standards, names of journals and divisions, historical bias) also may contribute to a limited view of chemistry. A belief that chemistry has a negative public image and is a field that lacks excitement may direct some practitioners of chemistry to choose not to identify themselves as chemists.

1-3. *What specific skills will employers want chemists and other practitioners of chemistry to have for successful careers in the future?*

Employers will continue to want students to have a strong chemistry background as well as the ability and drive to recognize and solve problems with a high degree of innovation and creativity. The ability to communicate, especially with those with backgrounds in different disciplines, the willingness to adapt to new situations with confidence, and the ability to learn over a lifetime are specific skills that practitioners of chemistry will need in order to have successful careers in the future. In addition, experience in proposal writing, the development of business plans, the management of groups and teams, and safety training will be very important for both academic and industrial employment. The ethical treatment of data, finances, reports, experimental living subjects, and fellow human beings also were identified as essential skills.

1-4. *As we look to the future of chemistry, what is perceived to be missing from students' current education?*

A list of topics that are perceived to be missing from students' current education is presented in the text box. While today's chemistry students learn the basics of our science, they also need to take courses that make them much more comfortable with multidisciplinary approaches. Conference participants were very supportive of efforts to provide students with opportunities to solve real-world problems, to gain exposure to other disciplines, and have more research-like experiences to enhance chemistry education and meet these needs.

Topics that are missing from students' current education in chemistry

Subject matter

- ☐ History and philosophy of science
- ☐ Ethics and civil responsibility
- ☐ Intellectual property rights
- ☐ Research-like laboratory experiences, particularly involving experimental design
- ☐ Links between qualitative and quantitative observation
- ☐ Toxicity and other environmental issues
- ☐ Integration of chemistry with other disciplines

Skills

- ☐ Business skills
- ☐ Information management skills, the development of the ability to discern good and bad information, and utilization of resources, especially electronic databases and journals
- ☐ Skill at communicating with both scientists and non-scientists
- ☐ Non-algorithmic and team-oriented problem-solving skills

Pedagogy

- ☐ Incorporation of relevant, real-world contexts to excite and motivate
- ☐ Recognition of the importance of different learning styles and educational approaches
- ☐ Promotion of learning with a passion
- ☐ Articulation that the problems to be faced by chemistry practitioners in the future will be complex and challenging
- ☐ Development of creativity
- ☐ Emphasis on the organizing principles of chemistry
- ☐ Using technology to teach and test

How is the content of chemistry education being changed at present?

Panelists: Brian Coppola, Arthur F. Thurnau Professor of Chemistry and Associate Department Chair for Curriculum and Faculty Affairs and Faculty Associate at the Center for Research on Learning and Teaching at the University of Michigan, **Susan Hixson**, program director, Division of Undergraduate Education (DUE), National Science Foundation (NSF), and **Lynn Melton**, Professor of Chemistry, University of Texas, Dallas.

Facilitator: Maureen Scharberg, San Jose State University

The second panel[1] and related breakout groups discussed how the content of chemistry education is currently being changed. The questions presented for consideration by panelists and in the breakout groups are listed below.

2-1. What types of reform efforts have been adapted and adopted, as well as sustained, in chemistry classrooms from community colleges to major research universities?
2-2. What are the current opportunities for curriculum reform?
2-3. How effective have current reform efforts been in changing the content of chemistry education?
2-4. What are the biggest challenges facing curricular reform in chemistry?

Susan Hixson described several NSF-DUE programs to illustrate the types of reforms in chemistry education that have occurred over the past ten years. DUE has granted significant funding to modify courses and laboratories as well as to create and/or adopt content from other disciplines or successful curricular models. Many NSF-funded professional development workshops for faculty focus on teaching methods and pedagogy as opposed to chemistry content. These areas are the current driving forces for faculty development. Innovative curriculum reforms need about 10 years to diffuse into practice, as reported by scholarly research on this subject. In general, recent projects have been successful in enhancing student retention in chemistry courses, as well as in promoting the formulation of student learning outcomes.

NSF has not identified a critical need for chemistry curricular reform in terms of content. Dr. Hixson reminded the participants that, since a large number of students are required to take chemistry courses as prerequisites for other fields of study, chemistry has a large captive audience. In addition, the traditional divisions and journals of ACS could be hindering efforts to work across subdisciplines. More remains to be discovered about how students best learn chemistry. At the same time, research journals will not publish curricular reform papers, so scientists are not reliably exposed to what already is known about how students best learn. No one single entity has responsibility for chemistry reform, making it a diffuse problem. She challenged participants to decide if the reform of chemistry education should be the responsibility of individuals, departments or a nationwide effort.

[1] At the conference Dr. Coppola and Dr. Hixson both responded to one question before moving to the next one. For consistency in the conference report, the major points of their presentations were organized as if they had spoken sequentially. Dr. Melton shared his thoughts after Dr. Coppola and Dr. Hixson presented their answers.

Brian Coppola suggested that modest progress has been made in reforming the methods used to teach chemistry, especially in broadening learning goals for students. Dr. Coppola believes that reform efforts have not been at all successful in changing the content of chemistry education. He noted that ACS recently made a significant contribution to the *status quo* by helping existing technical divisions remain intact. If ACS is truly serious about breaking down boundaries, it must be serious about eliminating traditional structures within its own organization. Viewing education reform broadly, some chemistry courses and topics have been reordered. He also recognized the trend to include research ethics and communication skills in the content of the undergraduate chemistry curriculum.

Dr. Coppola noted that, today, an enormous opportunity exists to convey and translate the molecular to supramolecular relationships between structure and function to our students and society. Dr. Coppola expressed the opinion that most chemistry faculty members often simply review the chosen text and its table of contents to develop the course syllabus. He believes that energy directed toward teaching and learning chemistry is not appreciated by the current academic culture and that the findings of this research are under utilized. Looking to NSF to solve these problems in not going to work, simply because NSF funds projects, not changes, and is conservative in its nature. We need to learn how to let educational goals drive content selection versus teaching operationally non-useful information.

Lynn Melton described the Doctor of Chemistry program in his department. The 20-year old program provides a broad foundation to learn material and the development of knowledge in an industry-relevant context and time scale (three to five years). The program also provides students with opportunities to gain industrial experience. The core courses in this program involve technical communication skills and problem solving skills. For the problem solving skills, students learn how to use to tools of chemistry as well as to ask the right questions. Dr. Melton believes that we should do a better job in preparing undergraduate chemists for employment, especially since approximately 50% of BA/BS chemistry graduates accept jobs rather than going on to graduate or professional schools. Problem solving skills are especially important in this regard. He explained that problem solving by a chemist involves receiving a problem in macroscopic language, solving the problem in microscopic terms, and then returning the answer in the macroscopic language that the requester understands.

Panel 2 Breakout Group Report

The breakout group discussions addressed the specific questions of the panel as well as the issues raised by the panelists' presentations.

2-1. *What types of reform efforts have been adapted and adopted, as well as sustained, in chemistry classrooms from community colleges to major research universities?*

The consensus from the breakout groups was that the panelists nicely summarized the types of the reform efforts, except for the recent efforts to incorporate green chemistry and principles of sustainable development into the chemistry curriculum.

2-2. *What are the current opportunities for curriculum reform?*

Breakout groups identified a number of areas where more concerted reform efforts are needed. These opportunities can be broadly categorized into opportunities for curriculum development and assessment, strategies in pedagogies for teaching chemistry, and professional development and support for faculty. With respect to curriculum development, conference participants suggested 1) developing an integrated science program and laboratories that are taught from an interdisciplinary perspective and 2) integrating discussions of the social impacts and responsibility of chemistry and chemists into the curriculum. They also suggested that the large number of topics in the undergraduate curriculum could be pared down by 1) identifying the minimum knowledge that must be acquired during the first year chemistry course or 2) making the first two years of undergraduate chemistry coherent and then developing parallel core courses for the next two years of advanced studies in chemistry. Conference participants felt that applications of computer information technology and faculty development could improve pedagogy. Computer technology could also facilitate the work of teams as they collaborate across multiple disciplines.

2-3. *How effective have current reform efforts been in changing the content of chemistry education?*

Breakout groups agreed that reform efforts had so far had a limited impact, but that some progress has been made at both the undergraduate and graduate levels. The changes that have occurred have been evolutionary rather than revolutionary. The extent of the reform is limited, however, because the faculty interested in these efforts are largely self-selecting; no incentive exists across the discipline to stimulate reform efforts. More collaboration among disciplinary societies could result in greater emphasis on these issues.

2-4. *What are the biggest challenges facing curricular reform in chemistry?*

The incentives to change course content include providing for the needs of other departments, as well as supporting collaborative and interdisciplinary activities. However, these incentives do not appear to be sufficient to overcome the considerable number of barriers to reform throughout the education system. Publishers, citing the choices made by faculty in selecting textbooks, want to retain traditional approaches. Instructors are sensitive to the fact that many undergraduate students will take standardized entrance examinations for graduate and professional schools, especially if they are planning a career in medicine.

The organization of academic departments and the divisional structure of chemistry create barriers to change within the chemistry community. Not all faculty recognize the need for change or adapt curricula to students' diverse learning styles. Instructors often want "ready-to-use" curriculum, often found with the traditional textbooks. The efforts of outstanding educators to make curriculum changes may not lead to favorable tenure, salary, and award decisions.

The lack of both individual and institutional incentives for change creates additional cultural barriers and challenges for curricular reform in chemistry. Currently, there is no perceived "impending disaster" in teaching chemistry and no obvious rewards for change. Graduates on all levels have been successful.

Implementation of curricular reform presents serious logistical challenges. Many institutions face a wide range of impediments including budgets, number of students, and the need to train faculty and teaching assistants. If the curriculum changes at a four-year college, it must be changed at the two-year college level.

Panel 2 noted that recent reform in chemistry education has largely been designed to take into account differences in student learning styles and in implementing new pedagogical approaches that reflect modern research on how students best learn chemistry. Additional reform efforts could focus on course content by introducing more interdisciplinary courses, labs and research opportunities; to pare down the large number of topics in the undergraduate curriculum; to integrate discussion of the social impacts of the science; and to embrace the computer revolution.

What are the new frontiers and interfaces of chemistry that impact upon our discipline?

Panelists: Paul Anderson, Vice President, Drug Discovery (retired) Bristol-Myers Squibb, and 1997 ACS President; **Arthur Ellis**, Director, Chemistry Division, National Science Foundation, on leave from University of Wisconsin-Madison where he is Meloche-Bascom Professor of Chemistry; and **Ronald Breslow**, University Professor of Chemistry, Columbia University; and 1998 ACS President.

Facilitator: David Malik, Indiana University Purdue University, Indianapolis

The third panel and related breakout groups focused on identifying the new frontiers and interfaces of chemistry. The panel discussion was to assess two objectives: 1) high-activity fields of importance where chemists will play a primary role now and into the future, and 2) the critical interfaces between chemistry and neighboring disciplines, and link these frontiers to opportunities in chemistry education. The following questions were addressed during this portion of the conference:

- 3-1. What are the frontiers of chemistry as defined by current discovery research today?
- 3-2. Which frontier areas will have the greatest impact on future chemistry?
- 3-3. Which frontier areas in other fields will have the greatest impact on future chemistry?
- 3-4. How should these frontiers and interfaces inform our choices of content that is appropriate for students in chemistry?

Paul Anderson focused his comments on medicinal chemistry and the areas of chemistry and related fields that will be most helpful to future success in the pharmaceutical sector. The major emphasis in this area continues to be on synthetic approaches for constructing or modifying complex molecules. Related advances in combinatorial chemistry, genomics, proteomics, and micro array (gene chip) technologies will play essential roles in advancing synthetic investigations and developing new methods.. Specific knowledge of biological principles and human metabolism are essential and at present are rarely a part of chemists' educational foundation.

Successful researchers of the future must be prepared for lifelong learning. They will have a broad and deep understanding of their field, be able to recognize and identify essential information, knowledge, or skills that are needed to solve a problem, and have a strategy to systematically expand and enhance their knowledge accordingly, especially into allied areas. The ability to understand the scientific literature at the interfaces of these areas is also important. Chemists of the future must be effective team players and contributors with an interest in advancing the objectives of the group. Competition is acceptable, but only in the spirit of advancing the goals and objectives of the team.

Art Ellis stressed the importance of nanotechnologies to the national interest. While most students receive instruction on the molecular foundations of chemistry, in most cases their knowledge of properties at the nanoscale is more limited. The nature of materials at macroscopic and microscopic levels must be better integrated into our knowledge base. The relationship of nanoscale technologies will rely on a solid grasp of quantum effects, more training in solid-state chemistry, and the association of macroscale properties with nanoscale structures. Imaging techniques will continue to play an important part in elucidating the structures and interactions of nanospecies.

Experiments have recently been introduced into the curriculum to synthesize nanoscale materials and demonstrate applications of cutting-edge technology. Future curricular changes need to be more responsive to evolving research needs and address the experiential base of our students. Applications of new technologies need to be included more comprehensively in the curriculum. Most students know about many of these advances, thus only their conceptual basis needs to be addressed. Ellis also noted that the societal implications of nanotechnology should not be ignored.

Ron Breslow pointed to the recent NRC report, *Beyond the Molecular Frontier* (NRC 2003a; see text box), which describes the grand challenges for chemistry and chemical engineering in the 21st Century. Dr. Breslow elected to focus on the technical issues of solid-state materials and nanoscale materials; the interface between chemistry and biology, medicine, and other fields; environmental and atmospheric chemistry; energy challenges for the future; and chemistry associated with national security. Dr. Breslow listed a series of challenges for faculty and institutions to consider towards improving the overall educational process. He cited the restricted extent of communication and discussion among the disciplines, further impeding their integration. Faculty should inform and inspire students with more challenging problems lying at the intersections of scientific disciplines. The educational system should present problems that we have not solved, or do not know how to solve, as challenges for the future generation. He detailed a number of proposals for improving chemistry education for graduate (Breslow, 2003) and undergraduate students (NRC, 2002).

Grand challenges for chemistry and chemical engineering in the 21st Century (NRC, 2003a)

1. Devise new ways to create and manufacture useful new substances.
2. Imitate nature.
3. Develop self-assembly of complex, organized structures and nanotechnology
4. Develop techniques for measurement and characterization
5. Advance chemical theory and modeling
6. Design greener processes and products
7. Fuel new energy sources
8. Enhance national and personal security
9. Public perception of chemistry
10. Support for chemistry research and education

Panel 3 breakout group report

The breakout group discussions addressed the specific questions of the panel as well as the issues raised by the panelists' presentations.

3-1. *What are the frontiers of chemistry defined by current discovery research?*

Conference participants benefited from the elegant summary of frontier areas provided in the NRC report, *Beyond the Molecular Frontier* (NRC, 2003a). Additional examples provided by participants include: solid state materials, genomics/proteomics, molecular devices such as motors, wires and switches, chemical information management tools, nanotechnology and its impact on information science, chemistry at extreme conditions, non-linear systems, and more connections to allied fields such as astrobiology, geology, and the environment.

3-2. *Which frontier areas will have the greatest impact on future chemistry?*

Many important frontier areas that could have a great impact on future chemistry are not yet known. Nevertheless, suggestions made by conference participants of current discovery frontiers in chemistry included the chemical interfaces of biomimetics, regenerative biology and synthetic body parts, complex and biocomplex systems, ultra small transmitting sensors and detectors, renewable feedstocks, and the educational consequences of emerging research on human learning.

3-3. *Which frontier areas in other fields will have the greatest impact on future chemistry?*

The participants departed from discussing solely technical content issues in allied fields and identified many additional topics important to chemistry to try to understand what forces might influence the knowledge base and the competencies and skills needed to conduct cutting-edge chemistry research. These topics included ethics, environmental impact assessments, the consequences of litigation, globalization, socioeconomic changes, and economics. Technical areas included biocatalysis, high-temperature semiconductors, computer technologies, interstellar molecules, energy transfer and storage, Bose-Einstein condensates and the consequences of the discovery of a new state of matter, and agriculture (genetics, natural product mimicry, photosynthesis).

3-4. *How should these frontiers and interfaces inform our choices of content that is appropriate for students in chemistry?*

Although the discipline of chemistry has been successful in many ways, it can be argued that instruction in the field hasn't adapted to the demands of today's workplace. The expanding frontiers of the discipline necessitate a broad and interdisciplinary view. Chemistry education must be broadened to make this transition easier and more responsive to the rapid new developments taking place today and tomorrow. The infrastructure of education has not led to rapid assimilation of new knowledge in the basic curriculum. A consistent theme in the discussions was the notion that we could use frontier areas as examples to extend the fundamentals of chemistry and highlight their relevance to students by providing a context for learning. Topics based on frontier research could be infused in core courses through the use of short modules, or could be presented as a series of short supplementary lectures or seminars for faculty and students alike. External internships in industry or government could provide better engagement and an introduction to research at the frontiers. One suggestion that emerged from the discussion was to engage faculty from other disciplines in teaching general chemistry courses to enhance the content and relevance of the course.

What is the irreducible minimum of chemistry (content, experiences, and skills) that students need to be effective chemists?

Panelists: George Wilson, Higuchi Distinguished Professor of Chemistry and Pharmaceutical Chemistry**,** University of Kansas; **Harold Kroto**, Royal Society Research Professor, University of Sussex, 1996 Nobel Laureate, 2003 President of Royal Society of Chemistry; **Terrence Collins,** Thomas Lord Professor of Chemistry and Director of Institute for Green Oxidation Chemistry**,** Carnegie Mellon University; and **Richard Zare**, Marguerite Blake Wilbur Professor in Natural Science at Stanford University.

Facilitator: Joseph Heppert, University of Kansas

The last session of the conference was intended to help the participants focus on the essential knowledge of chemistry and other disciplines and other skills and experiences that students should acquire while studying for a chemistry degree. Panel 4 and its attendant breakout sessions explored the following specific questions:

- 4-1. What foundations, principles and knowledge about the molecular sciences should we affirm as essential for all students receiving a degree in chemistry?
- 4-2. What crucial themes, foundations, principles and knowledge are underemphasized as a result of the structure of existing curricula in chemistry?
- 4-3. Beyond foundations, principles and knowledge, what experiences and skills in the molecular sciences are essential for students receiving a degree in chemistry?
- 4-4. What other experiences, skills and knowledge are essential for students receiving a degree in chemistry?

None of the panelists chose to directly address the overarching questions. However, each of the presentations highlighted specific issues in content, pedagogy or approaches to curriculum reform that the panelists identified as pertinent to the discussion topic.

George Wilson focused his remarks on the use of problem solving as a tool for the integration of chemical knowledge and skills. He described a problem-solving model for a third-year undergraduate instrumental analysis course at the University of Kansas where students work on teams to solve a specific, open-ended analytical problem. This course is designed to encourage students to integrate their knowledge by applying concepts and methods from many of the courses they have taken as undergraduates. In this instructional model, the instructor and teaching assistants adopt roles as consultants to the teams, providing advice on the cost effectiveness and safety of the chosen research design, and directing team members toward literature and resources that might help as they refine their analytical methods. Students enjoy the "reality" posed by of the laboratory problems they were assigned. They gained confidence in their abilities to define and solve research problems using their knowledge of chemistry. The instructor and teaching assistants noted that the quality of the projects completed was strongly dependent on how effectively the students worked together within a research team. The instructional team also found that implementing this course design was far more labor intensive than offering a traditional instrumental analysis course, and that fewer topics could be covered.

Harry Kroto's presentation focused on practical and everyday examples that reveal the intrinsic molecular/atomic nature and behavior of matter. He argued that one of the characteristics that differentiates chemists from average citizens is their subliminal awareness that the behavior of everything we observe is dependent on molecular and atomic behavior. We can and must create this awareness within the public by connecting society to 21st century chemistry. This effort involves the presentation of frontier chemical research to the public, and making explicit connections to the benefits that this research brings to society.

A central thesis of Kroto's presentation was that we are needlessly turning young students away from the sciences. All too often, we fail to capture student's imagination by not involving them in cutting edge science. He suggested that the survival of humanity depends on our ability to equip our students to accurately weigh the positive aspects of science, engineering and technology against the perceived disadvantages of these disciplines.

Terry Collins discussed the importance of sustainability ethics, toxicity and ecotoxicity in the training of chemists. He focused on the future involvement of chemists in building a sustainable, technologically based society. This theme grows out of a recognition that the human race is impacting the environment on a global scale, and has, thus far, chosen paths of economic and social development that are ecologically non-sustainable. In order to remedy this situation, society needs to commit to developing sustainable technologies, including 1) sources of safe energy, 2) renewable chemical feedstocks, and 3) processes that reduce pollution. Professor Collins argues that providing leadership in developing and implementing these changes will offer unique interdisciplinary research opportunities for chemists. Incorporating key concepts and skills for designing sustainable chemical processes into degree programs in chemistry is an important step toward realizing these opportunities. Chemists can no longer afford to avoid the ethical implications of the science and technologies that they produce, and future generations of chemists must be prepared with the skills and experiences needed to develop ecologically sustainable technologies.

Richard Zare focused his remarks on an examination of contemporary models of course reform and research-based pedagogical change that illustrate the great diversity of resources that already exist for improving chemistry degree programs. He emphasized the many different approaches chemists are adopting in curriculum reform efforts. He cited a range of curriculum reform projects and efforts to reorganize either the order in which content is presented in the undergraduate curriculum or the framework used to organize that content.

Zare asserted that many ways exist to teach chemistry. As a consequence, no rigid curriculum framework should be imposed on the chemistry community. Instructors must be free to use their knowledge of the students and the learning environment to assemble the content, pedagogy, and curriculum framework to create the most effective learning opportunities for students. He contended that introductory courses are usually not very effective in communicating the intellectual beauty, relevance, significance, and excitement of chemistry to students. He suggested that the greater challenge we face is to interest more students in pursuing careers in science, in general, and chemistry, in particular, rather than to devise introductory courses with an "ideal" curriculum content.

Panel 4 Breakout Group Report

The breakout group discussions addressed the specific questions of the panel as well as the issues raised by the panelists' presentations.

4-1. What foundations, principles and knowledge about the molecular sciences should we affirm as essential for all students receiving a degree in chemistry?

Participants used Peter Atkins' plenary presentation of an "irreducible minimum" as a beginning point for breakout group discussions. Groups proposed several amendments to Professor Atkins' summary of fundamental chemical concepts that are equally important to the practice of modern chemisty, such as the mechanisms of chemical reactions, the principle of microscopic reversibility, the scales of time and distance for atomic and molecular reactions, and the consequences of increasing molecular complexity. Groups also commented on the value to students of specific chemical information such as named organic reactions and the diversity of transition metal compounds.

Conference participants felt that chemistry education needs to convey the nature of chemistry as an empirical science and the manner in which chemical scientists perform experiments, interpret the results, generate concepts, create models, and solve problems. Students should learn how chemists seek to understand the macroscopic properties of matter by studying their composition and behavior on the molecular scale. Molecular motion is of paramount importance, as are such other subjects as chemical reactions and isomerism, and the distinct difference in nuclear reactions and chemical reactions. Also, all students should learn that chemists synthesize previously unknown elements, molecules, and materials, and systems made from these components. Finally, chemistry is important because it is a human activity that makes important contributions to solving societal problems in every material realm, including food, clothing, environmental sustainability, ethics, health, transportation, and communication.

Several conference participants noted that the undergraduate curriculum presents an unreasonably large collection of facts and concepts, especially given the recommended duration of study. Again recognizing the many audiences for chemistry education, it was suggested that the desired outcomes need to be defined before the content can be specified for a given audience and curriculum.

4-2. *What crucial themes, foundations, principles and knowledge are underemphasized as a result of the structure of existing curricula in chemistry?*

The discussion of this topic focused on both cutting-edge areas of chemical research that are not yet fully infused into the chemistry curriculum and some "big issue" concepts related to the nature and philosophy of chemistry as a discipline and profession. The participants indicated that these concepts should be represented prominently in curricula, because they help students to prepare for future careers in chemistry and to understand how chemistry can help address major societal needs. Examples of such cutting edge topics include genomics and proteomics, environmental chemistry and sustainability ethics, and materials chemistry. Similarly, major concepts deserving greater emphasis include the history of chemistry and the historic origins of foundational chemical concepts, the intellectual coherence and connectivity of chemistry and the philosophy and nature of chemistry.

4-3. Beyond foundations, principles and knowledge, what experiences and skills in the molecular sciences are essential for students receiving a degree in chemistry?

Conference participants identified many skills, abilities and experiences that students should acquire while in a chemistry degree program. Meaningful research experiences at various points along the pathway to a chemistry degree can include open-ended problem solving in laboratory experiments, or assigning team-oriented laboratory practica that help students develop an appreciation for the value of diverse approaches to ideas and problem solving. Industrial co-ops and internships are also valuable for providing students with alternative research experiences.

Examples of additional needed skills, abilities and experiences in the molecular sciences that are essential for the modern practitioner of chemistry are molecular and other chemical modeling, strategies for solving problems using the tools of chemistry, and creativity and innovation at the molecular level.

4-4. What other experiences, skills and knowledge are essential for students receiving a degree in chemistry?

These discussions focused on producing Ph.D. graduates with a broad educational background, including a range of experiences in the sciences, engineering and mathematics, and the study of philosophy, language, economics, and psychology. Such backgrounds would help new professional chemists obtain a deep appreciation of and an ability to work with scientists from other disciplines and a perspective of the ethical and social context of scientific research. Scientists with this training also are expected to be better able to address multiple audiences, especially nonscientists on the relevance of scientific research.

Since a degree in chemistry should be viewed as preparation for lifelong learning, students should develop skills that support their ability to construct understanding from 1) the literature, 2) their own research results, and 3) the cultural and social context of their studies. Consequently, chemistry graduates should be well grounded in various approaches to experimental design and statistical analysis of data, as well as in the use of information technology and evaluation of the quality of information resources.

Despite crowded curricula, time still needs to be found to portray the intellectual beauty, relevance, significance, and excitement of chemistry. Panel 4 participants thought that more emphasis is needed 1) on presenting the intellectual coherence and connections within the discipline; 2) on undergraduate research, 3) on the toxicity of chemicals and chemistry's role in supporting sustainable development, through, for example, green chemistry, and 4) computational modeling and linkages to modern research technology. They also thought that a solid background in chemistry fundamentals should be complemented by experiences that build communication skills, the ability to work in teams, and the ability to solve complex problems.

Conclusions

Conference participants identified several significant gaps between the content of current chemistry education and the practice of the discipline, and between the educational experiences of today's students and the integration of all sciences. While an "irreducible minimum" content of chemistry could be identified for teaching purposes, any reform based on this approach would not reform chemistry education well enough to reflect the current practice of chemistry. Course content should not be considered alone in planning an education program. To adequately reflect the *current practice* of chemistry, chemistry education must also reflect: 1) the convergence of chemistry with other disciplines, particularly biology and physics, 2) the impacts of improved mathematical and computational tools and of interactions through cyberspace, and 3) the relevance of the discipline by engagement with the broader society and accompanying promotion of high standards of ethics and environmental performance.

Exploring the Molecular Vision marks the beginning of a productive discussion on how to ensure that the content of chemistry education continues to attract talented students to the discipline, and that the education they receive prepares them for fulfilling careers. This workshop began to consider how chemistry education could be transformed to reflect the dominant research themes and current practices that are increasingly prevalent in the profession.

Conference participants were in broad agreement on several issues related to the need for curriculum change and the future of the chemistry profession. Areas of agreement include:

Current curriculum

1. Existing programs are producing graduates with excellent training and qualifications who are able to secure employment in the chemical sciences.
2. Most of the conceptual and factual knowledge needed to prepare a practitioner of chemistry is included in current degree programs.
3. The content (i.e., facts, concepts, skills and experiences) of existing chemistry curricula is not always representative of the current practice of chemistry.

The current curriculum has produced students of outstanding quality. They are successfully employed in industry, academia, and government. However, the preparation that students receive could be enhanced to reflect the vanishing boundaries between disciplines, powerful new experimental tools, the revolutionary impact of new mathematical and computational paradigms, and the opportunities for new interactions through cyberspace. All of these areas are increasingly important for successful careers in chemistry.

Educational reform efforts

4. In the process of education, the content of the chemistry curriculum cannot be divorced from the pedagogy employed in its instruction.
5. Past educational research and curriculum reform initiatives in chemistry have produced an important body of knowledge and instructional resources that should help to guide future curricular reform.
6. Although progress has been made, the number of college and university faculty participating in efforts to implement reform-based chemistry curricula must increase.

There was consensus that the details of pedagogy are critically important to chemical education and that pedagogy is difficult to avoid in any discussion of content reform. Conference participants recognized that the instructional tools, models and strategies employed in teaching are not synonymous with the knowledge, concepts, and skills of chemistry. The current curriculum is segmented into narrow, often unconnected and context-free subjects. The structure of many institutions in academia and professional organizations, and traditions in the scientific publishing industry contribute to this balkanization and are at odds with the trend toward increasing connections within chemistry and between disciplines. Most speakers at the conference recognized that extensive efforts have been made to understand how students best learn science and to develop and reform the chemistry curriculum. They acknowledged the need to use these resources to guide future reforms. The participants identified a need to expand the number chemistry faculty who are actively involved in implementing research-based teaching methods and curricula.

Participation in the profession

7. Content that demonstrates chemistry's relevance to society can help attract more diverse populations of students, faculty and researchers into the chemical sciences.

Conferees acknowledged, with concern the contrast between the national demographics and the composition of the science, technology and engineering workforce and the resulting need to attract a more diverse pool of students into chemistry degree programs. Extensive efforts to make chemistry courses more relevant to society may be a step in the right direction. We must emphasize the need to attract underrepresented students to advanced study in the sciences and to develop educational infrastructures that prepare these students to for success along this career pathway. A consistent theme in the conference discussions was the notion that frontier areas could be used as examples to extend the fundamentals of chemistry and highlight their relevance to students by providing a context for learning.

Preparation for the profession

8. Problem solving is one of the most empowering learning experiences for science students.
9. A deep knowledge of chemistry and the ability to pursue cutting-edge chemical research in teams have become even more central to innovation at the forefront of science and technology.
10. In addition to a strong background in chemistry, students should have many opportunities to master those skills that are essential for communicating across cultures, traditional roles, and disciplines.
11. Students need a wide range of experiences outside of science and technology to prepare them to be responsive to societal needs and concerns and to articulate the significance of the scientific enterprise to their fellow citizens.

Students need educational breadth that enables them to be effective citizens and to articulate the importance of technology to global development. Practitioners, of chemistry need an education that allows them to continually acquire new knowledge and skills as their research leads them to new frontiers in science. Conference participants were very supportive of efforts to provide students with opportunities to solve real-world problems to enhance chemistry education and become more comfortable with multidisciplinary approaches. Courses that help students communicate their ideas more clearly, manage effectively, behave ethically, work with colleagues and teams, and interact with their supervisors were all considered critical skills for success in the workplace. Ideally, their experiences in the university should prepare students for continuous learning throughout their lives.

Chemistry is not a science that we can attempt to constrain and control; rather, it is a dynamic reflection of the creativity, the interests of the many different scientists that practice it, and the educators that teach it. In order to accurately reflect and serve the needs of this discipline, the chemistry curriculum must also continue to be a vital and self-renewing entity. The ideas generated at Exploring the Molecular Vision were a good start to assessing why and how the content of chemistry education should and could change to better reflect the practice of modern chemistry. Although conference participants were in consensus about many issues in chemistry education, less agreement was evident on the importance of reforming the content of chemistry courses to address them. SOCED hopes that the conference marks the beginning of a productive discussion on how to ensure that what we teach students continues to attract talented students to the discipline, and that the education they receive prepares them for fulfilling careers in an ever-broadening range of employment. It is promising that most conference participants thought that continued discussion on these issues would be useful. A measure of the success of Exploring the Molecular Vision conference will be whether SOCED can convince others in the chemistry education community that this issue should be more thoroughly investigated. Continued discussions within the chemistry community are essential if the conference is to have a lasting impact on chemistry education.

Next Steps

SOCED does not recommend that the community undertake time intensive and transformational curriculum change without a clear understanding of well-defined needs. Recognizing that change has always taken place in education at an evolutionary, rather than revolutionary, pace, we nevertheless can set revolutionary goals for reinventing the content of chemistry education. Our efforts to meet these goals must be based on realistic analyses of need and expectations of what can be achieved.

While this conference addressed the need to reform the content of the chemistry curriculum, other issues related to the goals and outcomes of chemistry degree programs were not fully addressed. These issues, which could form the basis for continued exploration of chemistry education reform, include:

Academic issues

1. Do our current courses and degree programs accurately reflect our identity as a discipline?
2. Do our courses illustrate the value of having practitioners of chemistry (as opposed to practitioners of other disciplines) teach fundamental chemical principles?
3. Are we structuring our programs so that they attract a larger and more diverse population of students into chemistry?
4. Can the current structure of the undergraduate degree program accommodate all of our crucial goals and aspirations for chemistry majors?
5. Do our programs take the fullest possible advantage of the tools, strategies and resources that are available to improve student learning?
6. Do our programs serve the needs both of our majors, and of students majoring in other disciplines?
7. What constitutes adequate experience in research, particularly for students in undergraduate degree programs?
8. Are we providing the educational experiences that undergraduate and graduate students need to participate in research at the frontiers of chemistry?

Professional and social issues

1. Do our programs provide the knowledge, the technology and the well-trained professionals needed to support continued scientific innovation?
2. Are BS and PhD chemistry graduates prepared to participate as private sector and governmental leaders in a manner that will provide the maximum benefit to society?
3. Are our BS and PhD degree programs responding to society's need for experts in science, education, and business, and for scientifically literate social and political leadership?

Given constraints of time and resources both in chemistry degree programs and in projects intended to foster curriculum change, these and related questions can serve as a starting points for developing a framework for assessing our needs for curriculum reform and as a starting point for standards against which we can examine ongoing reform efforts. A future reform agenda should reflect the scientific, curricular, professional and social issues that are reshaping the nature of the chemical profession. The outcomes of the Exploring the Molecular Vision meeting challenge SOCED to collaborate with other stakeholders in the chemistry education community to thoroughly investigate these issues.

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Appendix B: Conference Participants

Paul Anderson, *Bristol Meyers Squibb (retired)*
Peter Atkins, *University of Oxford, Lincoln College*
Ronald Breslow, *Columbia University*
Judith Benham, *3M*
Charles Casey, *University of Wisconsin*
John Clevenger, *Truckee Meadows Community College*
Terrence Collins, *Carnegie Mellon University*
Melanie Cooper, *Clemson University*
Brian Coppola, *University of Michigan*
F. Fleming Crim, *University of Wisconsin*
Arthur Ellis, *National Science Foundation*
William Glaze, *Oregon Health & Science University*
David Gosser, *City College of New York*
Carlos Guttierez, *California State University, Los Angeles*
Sharon Haynie, *DuPont*
Susan Hixson, *National Science Foundation*
Thomas Holme, *University of Wisconsin Milwaukee*
Robert Hoyte, *State University of New York, Old Westbury*
Madeleine Jacobs, *American Chemical Society*
Harold Kroto, *University of Sussex*
Jay Labov, *National Research Council*
Cheryl Martin, *Rohm and Haas*
Thomas Meyer, *Los Alamos National Laboratory*
Lynn Melton, *University of Texas, Dallas*
Jeanne Narum, *Project Kaleidoscope*
Eli Pearce, *Polytechnic University*
Judith Ramaley, *National Science Foundation*
Elsa Reichmanis, *Lucent Technologies*
William Robinson, *Purdue University*
Mickey Sarquis, *Miami University*
Douglas Sawyer, *Scottsdale Community College*
Thomas Smith, *Rochester Institute of Technology*
Brock Spencer, *Beloit College*
Conrad Stanitski, *University of Central Arkansas*
James Stith, *American Institute of Physics*
John Westall, *Oregon State University*
George Wilson, *University of Kansas*
Ronald Webb, *Procter and Gamble Co*.
Richard Zare, *Stanford University*
Vera Zdravkovich, *Prince George's Community College*
Dorothy Zolandz, *National Research Council*

Organizing Committee

Daryle Busch, *University of Kansas*
Alan Elzerman, *Clemson University*
Joseph Heppert, *University of Kansas*
Morton Hoffman, *Boston University*
Donald Jones, *J&G Consulting*
David Malik, *IUPUI*
John Moore, *University of Wisconsin*
George Palladino*, University of Pennsylvania*
Maureen Scharberg*, San Jose State University*
Gordon McCarty, *Bayer Corp. (retired)*

Appendix C: Tabulated responses to surveys

The goal of the survey was to seek conference participants' views on an *irreducible minimum* from the vast content of chemistry that would best equip an ideally educated practitioner of chemistry. That irreducible minimum would include foundations, fundamental principles, concepts, and skills, as well as knowledge of experimental realms, factual arrays, models and theories.

Which specialty(s) most nearly describes you as a practitioner of chemistry?

- Analytical Chemist
- Bioanalytical Chemist
- Bioinorganic Chemist
- Biophysical Chemist
- Business
- Chemical Educator
- Chemical Physicist
- Computational Chemist
- Engineering
- Environmental Chemist
- Green chemistry
- Inorganic Chemist
- Macromolecular Chemist
- Materials Scientist
- Medicinal Chemist
- Not a chemist
- Organic Chemist
- Organometallic chemist
- Pharmaceutical Chemist
- Physics
- Physical Chemist
- Physical organic chemistry
- Polymer chemist
- Theoretical Chemist

Chemical subject areas identified by conference participants as components of the irreducible minimum

Molecules
- Molecular properties (structure, shape, dipole moments, bond energies)
- Bonding
- Molecular interactions
- Computational methods and modeling
- Atoms
- Periodic table, trends (size, electronic properties, isoelectronic systems)
- Atomic properties and interactions
- Energetics and Equilibria
- Enthalpy, entropy, and free energy
- Equilibria

Chemical Reactions
- Stoichiometry
- Hydrocarbons, heterocycles, and functional groups
- Reaction types (acid-base, redox, addition, elimination, substitution)

Reaction Kinetics
- Reaction rate laws and kinetic order
- Temperature dependence of kinetics
- Catalysis, enzyme-catalyzed reactions
- Thermodynamic vs. kinetic stability
- Molecular dynamics

Analyzing Molecules and Reactions
- Mass spectrometry
- Absorption and emission spectroscopy (UV, visible, infrared)
- NMR spectroscopy
- Diffraction (x-ray, neutron, electron)
- Separation methods: chromatography, electrophoresis, and centrifugation

Materials
- Properties and synthesis of materials

Biomolecules
- Building blocks: amino acids, nucleotides, carbohydrates, fatty acids
- Biopolymers: proteins, nucleic acids, polysaccharides
- Three-dimensional structure of biological macromolecules
- Synthesis

Water and Aqueous Solutions
- Ionic compounds in aqueous solutions
- Acid-base equilibria, pH, pK.

Other topics
- The relation of structure and function (several)
- Relating macro properties to particulate level structure (several)
- Toxicity
- Posing good problems/problem solving
- Quantum concepts (several)
- Surface Chemistry, chemistry at the interface
- Intradisciplinary connections
- Teams/teamwork
- Experimental design (several)
- Sustainability
- Ethics
- Varied teaching approaches
- Statistics/measuring
- Bio-geochemical cycles

Appendix D: Conference Agenda

Friday, June 27

6:00 – 7:00 pm **Registration and Welcoming Reception.**

7:00 – 10:00 pm *[Dinner]*

Science and Education.

Eli Pearce, Polytechnic University. "Reinventing Chemical Education."

Jay Labov, National Research Council. "Achieving the Molecular Vision: The Whole Can Be More Than The Sum of Its Parts."

Discussion.

Saturday, June 28

7:20 – 8:00 am *[Breakfast]*

8:00 – 8:20 am **Introduction and vision.**

Daryle Busch, Society Committee on Education

Logistics.

Sylvia Ware, American Chemical Society

8:20 – 9:00 am **Chemistry and Education.**

Judith Ramaley, National Science Foundation. "Chemistry 2010: Revamping the undergraduate experience."

Discussion.

9:00 – 10:10 am **Panel 1.** ***Who are the practitioners of chemistry, and what are their educational needs?***

Facilitator: Morton Hoffman, Boston University

William Glaze, Oregon Health and Science University

Thomas Meyer, Los Alamos National Laboratory

Elsa Reichmanis, Lucent Technologies

Discussion.

10:10 –10: 25 am *[Coffee break]*

10:25 – 11:25 am Breakout groups.

11:25 – 12:10 pm ***[Lunch]***

12:10 – 12:40 pm Report from breakout groups.

12:40 – 1:50 pm	**Panel 2**. ***How is the content of chemistry education being changed at present?*** *Facilitator*: Maureen Scharberg, San Jose State University Brian Coppola, University of Michigan Susan Hixson, National Science Foundation Lynn Melton, University of Texas Dallas **Discussion.**
1:50 – 1:55 pm	*[Transition to breakout rooms]*
1:55 – 2:55 pm	**Breakout group #2.**
2:55 – 3:10 pm	*[Refreshment break]*
3:10 – 3:40 pm	**Report from breakout groups.**
3:40 – 4:50 pm	**Panel 3.** ***What are the new frontiers and interfaces of chemistry that impact upon our discipline?*** *Facilitator*: David Malik, Indiana University-Purdue University Indianapolis Paul Anderson, Bristol Meyers Squibb (retired) Ronald Breslow, Columbia University Arthur Ellis, National Science Foundation **Discussion.**
4:50 - 4:55 pm	*[Transition to breakout rooms]*
4:55 – 5:55 pm	**Breakout group #3.**
5:55 – 6:10 pm	*[Break to prepare reports]*
6:10 – 6:40 pm	**Report from breakout groups.**
6:40 – 10:00 pm	*[Dinner]* Peter Atkins, University of Oxford. "Chemistry: what really matters?" **Discussion.**

<u>Sunday, June 29</u>

7:20 – 8:00 am	*[Breakfast]*
8:00 – 8:10 am	**Logistics.** Sylvia Ware, American Chemical Society
8:10 – 9:30 am	**Panel 4.** ***What is the irreducible minimum of chemistry (content, experiences and skills) that students need to be effective chemists?*** *Facilitator*: Joseph Heppert, University of Kansas Terrence Collins, Carnegie Mellon University Harold Kroto, University of Sussex George Wilson, University of Kansas Richard Zare, Stanford University **Discussion.**
9:30 – 9:35 am	*[Transition to breakout rooms]*
9:35 – 10:35 am	**Breakout group #4.**
10:35 – 10:50 am	*[Coffee break]*
10:50 – 11:20 am	**Report from breakout groups.**
11:20 – 1:00 pm	**Integration.** *Final discussion and next steps.* *Facilitator*: Daryle Busch, University of Kansas
1:00 pm	**Adjourn.** Box lunches available for participants.