1
Chemistry Education and Human Activity

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1.1
Overview

The context for the book *Chemistry Education: Best Practices, Opportunities, and Trends* is set by this opening chapter, which asserts that the difference between historical "chemical education" and contemporary "chemistry education" is human activity. Tetrahedral chemistry education is reviewed as a visual and conceptual metaphor that was created to emphasize the need to situate chemical concepts, symbolic representations, and chemical substances and reactions in important human contexts. Three dimensions of human activity that require strong emphasis for educational practice to meet the learning needs of students are developed: (i) the human activity of learning and teaching chemistry; (ii) the human activity of carrying out chemistry; and (iii) the human activity that has imprinted itself in such a substantial way on the chemistry of our planet that it has defined a new geological epoch. Introducing chemistry content through rich contexts is proposed as one evidence-based approach for weaving all three of these dimensions of human activity into the practice of teaching and learning chemistry at secondary and post-secondary levels.

1.2
Chemistry Education and Human Activity

The term "chemical" education, which I encounter every day, has a long and storied history. I belong to the "chemical" education divisions of both the Chemical Institute of Canada and the American Chemical Society (ACS). On my bookshelf is the Journal of "Chemical" Education, and I access resources from the "Chemical" Education Digital Library. I regularly attend "chemical" education conferences and visit "chemical" education centers. In my professional circles, research and practice is supported by "chemical" education foundations, and exemplary practitioners of the art, science, and craft of teaching chemistry receive awards for contributions to "chemical" education.

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Yet, by design, the title of both this chapter and this book uses the word “chemistry” instead of “chemical” education. Should the two terms be used interchangeably, as is so often done?

The difference between chemical education and chemistry education is human activity.

How should the modern profession of “chemistry” education differ from historic “chemical” education? The term “chemical” education accurately conveys that at the heart of this domain of education are substances: their structures and properties, and the reactions that change them into other substances. But, beyond chemicals, human activity is central to (i) teaching and learning chemistry, (ii) the practice of chemistry in laboratories and industry, and (iii) the use and reactions of chemical substances by ordinary people. This opening chapter in *Chemistry Education: Best Practices, Opportunities, and Trends* asserts that chemistry educators should embed an understanding of all three of these different types of human activity into their practices of teaching and learning about the structures, properties, and reactions of chemical substances. And consistently using the term “chemistry education” as a more authentic descriptor than “chemical education” is a good starting point in conveying to students and the public the centrality of human activity in our professional domain.

1.3
A Visual Metaphor: Tetrahedral Chemistry Education

As chemistry educators, are we stuck in some of the historic practices of “chemical” education that we may have experienced as students? Have we narrowed our field of vision to presenting the intricate details of chemical substances and their reactions? Do our course and program learning objectives sufficiently incorporate students’ need to understand why they should care about the “chemical” content they receive? Understanding how to effectively present “chemistry” authentically to students, including the multifaceted human connections of the discipline, has motivated an important thread of my research and practice for over a decade. Knowing that metaphors can influence as well as reflect practice, I have encouraged stronger emphasis on human activity in chemistry education through a new visual and conceptual metaphor – tetrahedral chemistry education [1].

How does a tetrahedral shape relate to the move from “chemical” to “chemistry” education? Chemistry educators have shown that students need to encounter chemistry at different thinking levels to obtain a rich understanding of chemical substances and reactions. To address human learning patterns, Johnstone, Gabel, and others [2] have proposed three widely accepted thinking levels needed to learn chemistry: the symbolic or representational (symbols, equations, calculations), the macroscopic (tangible, visible, laboratory), and the molecular or submicroscopic. These are often represented as a triangle of thinking levels required for mastery of chemistry. As shown in Figure 1.1, the visual metaphor of tetrahedral chemistry education extends the triangle of levels of engaging chemistry into a third dimension, in which the fourth vertex represents the human

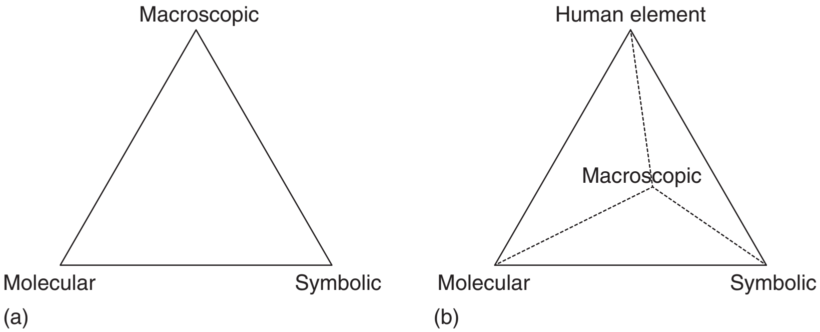


Figure 1.1 Tetrahedral chemistry education (b), as an extension of the triangle of thinking levels (a), making the focus on human activity in learning and teaching chemistry more visible and intentional.

contexts for chemistry. This new visual dimension emphasizes the need to situate chemical concepts, symbolic representations, and chemical substances and processes in the authentic contexts of the human beings who create substances, the culture that uses them, and the students who try to understand them. The tetrahedral chemistry education metaphor has been adapted and extended in various initiatives to articulate and support approaches to curriculum that foreground the human contexts for chemistry [3].

1.4
Three Emphases on Human Activity in Chemistry Education

What sorts of human activities are implied by changing the description of "chemical" to chemistry education, and emphasized by invoking the metaphor of tetrahedral chemistry education? What implications might more formal and systematic emphases on the human element have on learning through and about chemistry? How does emphasizing the human activity of chemistry flow from and inform research findings? Is our developing understanding of how the scale of human activity impacts the chemistry of our planet's life support systems adequately reflected in curriculum and pedagogy?

In this opening chapter, we take a 10-km high view of chemistry education to articulate three dimensions of human activity that should receive strong emphases in our professional efforts to ensure that our practice meets the learning needs of chemistry students: (i) the human activity of learning and teaching chemistry; (ii) the human activity of carrying out chemistry; and (iii) the human activity that has imprinted itself in such a substantial way on the chemistry of our planet that it has defined a new geological epoch. Our analysis will focus on chemistry education at the upper secondary and introductory post-secondary levels, with examples of effective practices that weave these emphases through both curriculum and pedagogy.

1.4.1
The Human Activity of Learning and Teaching Chemistry

Johnstone [4] highlights some of the results of paying too much attention to the "chemical" and not enough to the "education" part of chemical education. He suggests that current educational practice often clusters ideas into indigestible bundles, and that theoretical ideas are not linked to the reality of students' lives. The result: "chemical" education that is irrelevant, uninteresting, and indigestible, leading to student attitudes that range from not being able to understand to indifference about arriving at understanding.

Gilbert's [5] review of the interrelated problems facing chemical education over the past two decades reinforces Johnstone's critique, suggesting that students experience (i) an overload of content, (ii) numerous isolated facts that make it difficult for students to give meaning to what they learn, (iii) lack of ability to transfer conceptual learning to address problems presented in different ways, (iv) lack of relevance of knowledge to everyday life, and (v) too much emphasis on preparation for further study in chemistry rather than for development of scientific literacy.

Tetrahedral chemistry education implies identifying and meeting the needs of the diverse groups of students we serve with chemistry courses, and a transition from an emphasis on teaching to what research has to say about effective strategies and approaches to help students learn, and to learn chemistry.

What aspects of the human activity of teaching and learning chemistry need ongoing attention? Consider an example.

1.4.1.1 Atoms or Learners First?

Fifteen years after Johnstone's call to "begin where students are [2a]," vestiges of "chemical" rather than "chemistry" education remain. One example can be found when educators take quite literally the "atoms-first" approach to teaching chemistry. While it is difficult to find consistent definitions of this "new" approach, and the research evidence supporting it is very limited [6], the term is often used to describe a flow of ideas that begins with introducing the simplest building blocks of matter, and then assembles those first blocks of knowledge into more complex pieces, to eventually reach the point where the relevance of that understanding becomes evident to a student. The approach is summarized in the promotion for a 2013 chemistry textbook:

> The atoms-first approach provides a consistent and logical method for teaching general chemistry. This approach starts with the fundamental building block of matter, the atom, and uses it as the stepping stone to understanding more complex chemistry topics. Once mastery of the nature of atoms and electrons is achieved, the formation and properties of compounds are developed. Only after the study of matter and the atom will students have sufficient background to fully engage in topics such as stoichiometry, kinetics, equilibrium, and thermodynamics … [7]

Atoms-first may have roots over a half-century old in the work of Linus Pauling, who, in the first edition (1950) of his much-emulated *College Chemistry* suggests a similar flow of ideas:

> In this book I begin the teaching of chemistry by discussing the properties of substances in terms of atoms and molecules … [8]

The flow of ideas in putting atoms first is logical, consistent, and perhaps even elegant to the instructor who is an expert in chemistry and who already sees in his/her mind's eye important and motivating applications that will provide the reward for obtaining and stacking the first blocks of knowledge. But to a novice learner who is asked to wait to see the beauty and significance of the whole until the key pieces of knowledge are in place, the approach easily leads to fragmented understanding and difficulty in seeing the relevance of the knowledge learned. A parallel to "atoms first" in architecture education might be a deferred-gratification "sand-first" approach, where beginning architecture students study in sequence the details of sand, mortar, aggregate, rebar, and slabs of concrete, before finally seeing, perhaps half-way through a course, the exquisite building that motivates the vision and passion of an architect [9]. Perhaps atoms and other isolated "chemical" building blocks need to come second, after first motivating learners with the beauty and importance of the whole, based on an understanding of their diverse needs for learning chemistry.

> Science is built up with facts, as a house is with stones. But a collection of facts is no more a science than a heap of stones is a house.
>
> Henri Poincaré, La Science et l'hypothèse [10]

1.4.1.2 **Identifying Learners and Designing Curriculum to Meet Their Needs**

The learning needs of post-secondary chemistry students cannot possibly be met without first identifying who populates chemistry courses at the first-year university level. In first-year university chemistry courses in North America, an overemphasis is often placed on providing all of the foundational pieces for the few students who major in chemistry, rather than for the majority of students who will pursue careers in health professions, engineering, or other areas. Perhaps, practice here, too, has been shaped by Linus Pauling's influential approach in his 1950 textbook, who seems to have considered those who weren't majoring in chemistry as a bit of an after-thought:

> Although General Chemistry was written primarily for use by students planning to major in chemistry and related fields it has been found useful also by students with primary interest in other subjects … [8]

Effective educational practice requires understanding who the students are who take chemistry, and ensuring that learning objectives are formulated to meet the needs of the many students who won't again darken the door of a chemistry course or lab, as well as those going on to study chemistry.

1.4.1.3 Effective Practices in the Human Activity of Learning and Teaching Chemistry

Re-hybridizing learning toward tetrahedral chemistry education that attends thoughtfully to the human activity of learning and teaching chemistry requires much more than tinkering with curriculum. Rather, systemic efforts to deliberately design learning environments, curriculum, pedagogy, and physical spaces are all needed to enrich the experiences of learners. In the past several decades, the community of educators has taken monumental strides to pay more attention to the "education" part of "chemical education." This includes efforts to identify and understand the learning needs of all students studying chemistry, to create learning communities, and to implement both curriculum and pedagogical strategies that lead to more active and engaged learning. It would be impossible to adequately summarize here the approaches and initiatives that have emerged, but there is now substantial literature supporting effective practices on the human activity of learning and teaching chemistry.

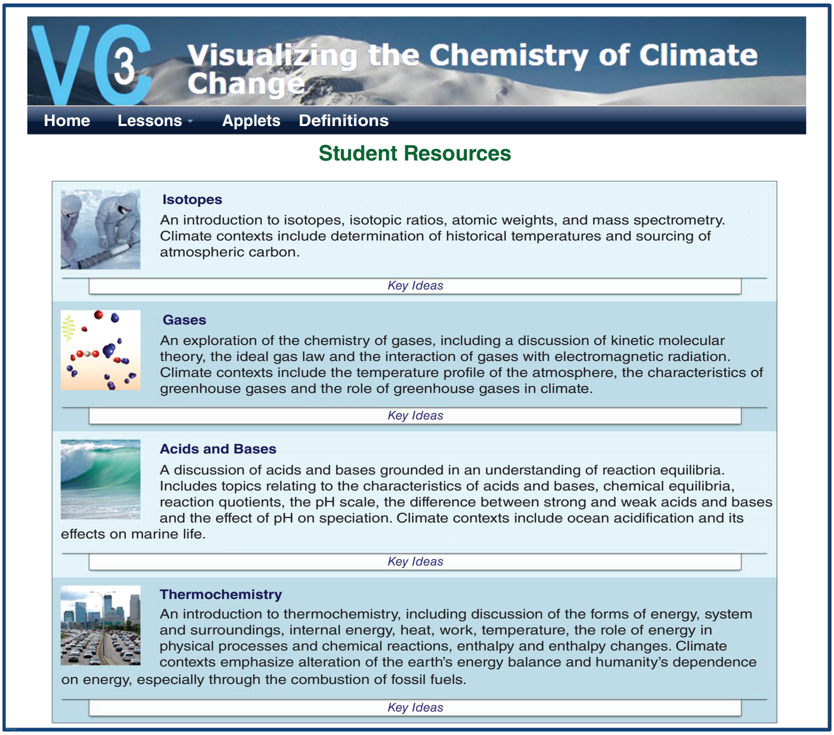
A review of that literature suggests helpful practices to enrich experiences of learning chemistry [11], including (i) understanding the student's prior conceptual understanding and developing validated inventories and strategies to identify and address misconceptions; (ii) using models for learning that account for different learning styles and limits to cognitive load; (iii) motivating students; (iv) engaging students with active and collaborative instruction and building and supporting intentional learning communities; (v) developing curriculum that connects to the lived experience of students and societal needs; (vi) implementing strategies for faculty professional development; and (vii) integrating into education the responsible and ethical practice of science. Many of these strategies and practices are the focus of later chapters of this book.

1.4.1.4 Identifying and Eliminating Worst Practices as a Strategy?

A U.S. National Academies National Research Council report on linking evidence and promising practices in reforming Science, Technology, Engineering, and Mathematics (STEM) education [12] reinforces effective practices in many of the areas listed above. The report identifies challenges in disseminating best practices beyond individual faculty members in undergraduate institutions. It suggests that, in addition to improving student learning and faculty teaching, it may be helpful to focus on improving student learning productivity. The greatest gain in aggregate student learning in STEM might be achieved, suggests the report, not by insisting on adopting optimal teaching practices in every classroom, but by identifying and eliminating the worst practices in each classroom. For example, substantial gains in student learning might result from encouraging the majority of STEM faculty members who only lecture to use *any form* of active learning, rather than unrealistically insisting that the optimal practices of these instructional approaches be adopted.

1.4.1.5 Exemplar: Emphasizing the Human Activity of Learning and Teaching Chemistry

Visualizing the Chemistry of Climate Change (VC3) [13] is one example of an evidence-based approach to implementing reform for introductory university chemistry courses, based on an analysis of the motivational and learning needs and conceptual understanding of students. Starting with the recognition that interdisciplinary understanding of complex systems is fundamental to understanding modern science, the end goal of VC3 is to provide tested interactive digital learning resources to support chemistry instructors in adopting active-learning pedagogies that situate cognition in authentic science practice and a particularly important context – global climate change. VC3 has developed an interactive set of resources, targeting first-year university chemistry students and teachers, with a triptych of goals, to (i) exemplify science education for sustainability, (ii) improve the understanding of climate change by both undergraduate students and faculty members, and (iii) provide resources to support pedagogical reform by modeling how chemistry topics can be contextualized to enhance student motivation and learning.



Student Resources

Isotopes
An introduction to isotopes, isotopic ratios, atomic weights, and mass spectrometry. Climate contexts include determination of historical temperatures and sourcing of atmospheric carbon.

Gases
An exploration of the chemistry of gases, including a discussion of kinetic molecular theory, the ideal gas law and the interaction of gases with electromagnetic radiation. Climate contexts include the temperature profile of the atmosphere, the characteristics of greenhouse gases and the role of greenhouse gases in climate.

Acids and Bases
A discussion of acids and bases grounded in an understanding of reaction equilibria. Includes topics relating to the characteristics of acids and bases, chemical equilibria, reaction quotients, the pH scale, the difference between strong and weak acids and bases and the effect of pH on speciation. Climate contexts include ocean acidification and its effects on marine life.

Thermochemistry
An introduction to thermochemistry, including discussion of the forms of energy, system and surroundings, internal energy, heat, work, temperature, the role of energy in physical processes and chemical reactions, enthalpy and enthalpy changes. Climate contexts emphasize alteration of the earth's energy balance and humanity's dependence on energy, especially through the combustion of fossil fuels.

Figure 1.2 Visualizing the Chemistry of Climate Change (*www.vc3chem.com*) interactive electronic resources to introduce topics in general chemistry through climate contexts. (Figure courtesy of the King's Centre for Visualization in Science.)

The VC3 initiative (Figure 1.2) has been implemented in five phases: (i) mapping the correlation between climate literacy principles and core first year university chemistry content; (ii) documenting underlying science preconceptions and misconceptions, developing an inventory of chemistry concepts related to climate change, and validating instruments that make use of the inventory to assess understanding; (iii) developing and testing peer-reviewed interactive digital learning objects related to climate literacy principles with particular relevance to undergraduate chemistry; (iv) piloting the materials with first-year students and measuring the change in student understanding of both chemistry and climate science concepts, relative to control groups not using the materials; and (v) disseminating the digital learning objects for use by chemistry educators and students. An overview of the VC3 approach and a detailed example of one of the four VC3 topics developed to date at the King's Centre for Visualization in Science is given in Section 1.5.1 of this chapter.

1.4.2
The Human Activity of Carrying Out Chemistry

A second way for chemistry educators to emphasize the human element is by attending to the scholarship that asks whether the chemistry taught and learned in classrooms authentically reflects the practice of chemistry. Research on portrayals of science in formal curricula has documented student misconceptions about scientists, how science develops over time, and the nature of scientific knowledge [14]. The stakes are high in addressing these misconceptions, as chemistry students' understanding about the nature of science will influence their attitudes toward learning chemistry and their ability to react thoughtfully and critically to scientific claims. Talanquer [15] suggests that the unique features of chemistry as a discipline add complexity to the efforts to categorize the authenticity of portrayals of how chemistry is carried out. In addition to observing, explaining, and modeling, as has been the case for many other sciences, chemistry is also about creating new substances, designing new synthetic and analytical processes, and analyzing and transforming material systems. Deep understanding of science, including chemistry, requires understanding the evidence for theories and the discipline's underlying assumptions and methods [14].

Tetrahedral chemistry education emphasizes the coherence between the rich human activity of carrying out chemistry and the portrayals of that activity in classrooms and laboratories. Chemistry students should have an authentic understanding of where ideas and theories come from, how they develop over time, and how they connect to observations about the world. They should frequently engage the question: "How do we know what we know?" in addition to "What do we know?"

1.4.2.1 Explicit and Implicit Messages about the Nature of Chemistry

Without overt attention to the authenticity of how chemistry is portrayed, "chemical" education can introduce misconceptions about science as an intellectual and social endeavor. But one challenge in analyzing the authenticity of portrayals of the human activity of carrying out chemistry is that implicit, as well as explicit, messages about the nature of science are communicated to students as they learn the "facts" of chemistry. By recognizing and countering unauthentic messages, chemistry educators can seize opportunities to paint a picture of chemistry as a creative science [16]. Non-authentic portrayals are introduced or reinforced in a variety of unexamined and implicit ways including static, contrived, and predetermined laboratory exercises; presentation of chemistry as isolated facts to be remembered, without a genuine understanding of how chemists develop explanations; lack of attention to where ideas come from and how they change over time; insufficient attention to the processes and tools chemists use to analyze, interpret, and apply data; neglect to highlight the imaginative process that is such a central part of "thinking like a chemist"; and failure to mention the ethical choices chemists and chemistry students make about how knowledge is used [17].

While practice has improved over the past decade, some textbooks still present the naïve and distorted caricature of a single hypothetico-deductive method used to carry out chemistry, often referred to as *the scientific method*. More authentic portrayals of how chemistry is carried out will leave students with an understanding that science grows through communities of practice that stand on the shoulders of prior understanding and that are influenced by a wide variety of human influences, including societal pressures and the availability of research funding. Understanding in chemistry develops in fits and starts, involves a mix of inductive, deductive, and abductive [18] methods, and at times is moved dramatically forward by chemists willing to challenge existing paradigms, and occasionally by serendipitous discoveries. Simplistic or distorted caricatures of science not only create misconceptions about the nature of science, but also make it difficult for human learners to see themselves as meaningful participants in carrying out science [19].

> The images that many people have of science and how it works are often distorted. The myths and stereotypes that young people have about science are not dispelled when science teaching focuses narrowly on the laws, concepts, and theories of science. Hence, the study of science as a way of knowing needs to be made explicit in the curriculum… not all of the historical emphasis should be placed on the lives of great scientists, those relatively few figures who, owing to genius and opportunity and good fortune, are best known. Students should learn that all sorts of people, indeed, people like themselves, have done and continue to do science.
>
> American Association for the Advancement of Science, Project 2061 Benchmarks [20]

1.4.2.2 **Breathing the Life of Imagination into Chemistry's Facts**

Implicit messages that convey less-than-authentic understandings of science are ubiquitous, and are found beyond the opening chapters of chemistry texts that outline the methods of science. But they are sometimes difficult to spot, due to entrenched patterns for sequencing instruction in "chemical" education. The flow of ideas in many learning resources at both the secondary and first-year post-secondary levels starts with facts and concepts to be learned – often presented in isolation from the evidence that underlies those facts, and then moves to applications of those concepts. A good example is found in treatment of structure and bonding of molecular substances, where the sequence of learning often *begins* with theories of bonding, such as hybridization and Valence Shell Electron Pair Repulsion (VSEPR) theory, *before* any evidence of experimental geometries, and without discussion of the nature and complementarity of different theories and models to explain that experimental evidence. As a result of such sequencing of ideas, and sometimes because of explicit language to that effect, students develop misconceptions. They may come to believe, for example, that carbon atoms in molecules of alkanes are tetrahedral *because* they are sp^3-hybridized. Assessment questions often ask students to list the hybridization of certain atoms in molecules or their "VSEPR geometries" without overtly referencing hybridization and VSEPR geometries as powerful, but limited models for making sense of experimental data.

A learning sequence for an introductory university chemistry course that presents a more authentic view of how chemists arrive at their understanding is to start with the activity of human beings who provide experimental evidence for structure and bonding, using techniques such as infrared spectroscopy (evidence for connectivity patterns in functional groups), mass spectrometry (evidence for molecular formulas), X-ray crystallography (bond lengths and bond angles), and nuclear magnetic resonance (NMR) spectroscopy (map of the C–H framework of organic compounds), and then to convey a sense of how chemists *imagine complementary scientific models* to explain that evidence [21]. Such a sequence can help students see both the power and limitations of models: the imaginative and creative processes that lead to robust explanations, and to avoid equating models with reality. In his 1951 Tilden Lecture, Oxford University Chemist Charles Coulson, whose work played an important role in developing our current theories of chemical bonding, describes the result of conflating models with experimental evidence, when considering a simple chemical bond, such as the C–H bond in methane:

> Sometimes it seems to me that a bond between two atoms has become so real, so tangible, (and) so friendly that I can almost see it. And then I awake with a little shock: for a chemical bond is not a real thing; it does not exist; no-one has ever seen it, no-one ever can … Hydrogen I know, for it is a gas and we keep it in large cylinders; benzene I know, for it is a liquid and we keep it in bottles. The tangible, the real, the solid, is explained by the intangible, the unreal, (and) the purely mental. Yet that is what chemists are always doing … [22]

Coulson goes on to articulate the importance of recognizing the human imagination as an integral part of chemistry sense-making.

> With us, as Mendeleev said, the facts are there and are being steadily accumulated day by day. Chemistry certainly includes all the chemical information and classification with which most school test-books are cluttered up. But it is more; for, because we are human, we are not satisfied with the facts alone; and so there is added to our science the sustained effort to correlate them and breathe into them the life of the imagination.
>
> Charles A. Coulson, 1951 Tilden Lecture [22]

All chemistry educators, knowingly and unknowingly, communicate messages about the nature of science. However, the messages students receive are often unrecognized or unexamined [14]. Substantial efforts are being taken in several countries to ensure that students develop an authentic understanding of science as a human endeavor [23]. The United States Next Generation Science Standards elaborate on this with recommendations that the following aspects of the nature of science should be communicated implicitly and explicitly in science classrooms [24]:

- Scientific investigations use a variety of methods.
- Scientific knowledge is based on empirical evidence.
- Scientific knowledge is open to revision in light of new evidence.
- Scientific models, laws, mechanisms, and theories explain natural phenomena.
- Science is a way of knowing.
- Scientific knowledge assumes an order and consistency in natural systems.
- Science is a human endeavor.
- Science addresses questions about the natural and material world.

1.4.2.3 Exemplars: Emphasizing the Human Activity of Carrying Out Chemistry

- McNeil [25] uses an innovative pedagogical strategy for moving university students from algorithmic application of "rules" for structure and bonding to deeper conceptual understanding that emphasizes the strength and limitations of complementary models to explain a large set of experimental observations. He divides students into two or more learning communities (e.g., a valence bond theory community and a molecular orbital theory community), each of which is required to persuasively explain pertinent data using *only* their assigned bonding theory. "Dueling bonding theories" result, as members of each learning community try to convince the others that their theory will better explain particular examples of data such as experimental geometries, bond strengths, magnetic properties, chemical reactivity, spectroscopic data, and chemical reactivity. Problem-solving, communication, and higher order skills are demonstrated as the groups attain deeper conceptual understanding, and the strength and limitations of models to explain evidence.
- The first-year university chemistry learning resource, *Chemistry: Human Activity, Chemical Reactivity* [21], uses two opening-chapter narratives to

introduce the power of modern chemistry to solve important problems and improve the quality of life while giving an authentic glimpse into the way modern chemistry is carried out in research groups and laboratories. Students are introduced to chemistry through the stories of David Dolphin, a Canadian chemist who has designed and made new substances that have improved the quality of life for over a million people suffering from cancer or eye disease, and Gavin Flematti, an Australian chemist who, while he was a postgraduate student, identified a compound in smoke that causes plant seeds to germinate after a forest fire. Flematti then found a way to make this compound in the laboratory. Modern techniques such as spectroscopy and chromatography are introduced through these human activity stories, and students obtain a feel for the time scale involved in chemical discoveries, as well as the role of both prior knowledge and serendipity. Then, each subsequent unit in the textbook begins with a relevant "rich context" that is designed to trigger student interest and the need to know more about the concepts covered in that chapter. Section 1.5.1 provides a detailed example.

1.4.3
Chemistry Education in the Anthropocene Epoch

> Two billion years ago, cyanobacteria oxygenated the atmosphere and powerfully disrupted life on earth … But they didn't know it. We're the first species that's become a planet-scale influence and is aware of that reality.
>
> Andrew Revkin, New York Times [26]

With awareness of the reality of the planet-scale influence of our species comes responsibility by educators to communicate, over educational levels and across disciplines, fundamental ideas about the fit between humans and our habitat. A compelling case for a new emphasis on human activity in chemistry education comes from considering the paradoxical ways in which chemistry has affected (usually for the better) virtually every aspect of human life, while at the same time comprehending that the scale and nature of modern human activity since the Industrial Revolution, aided by those very developments in chemistry, has fundamentally changed the chemistry of planet Earth.

What is the scope and magnitude of this human activity, linked to chemistry? The scientific community is moving toward accepting the term "Anthropocene Epoch" as an appropriate chronological term on the geological time scale to describe the transition from the Holocene Epoch to a new epoch that is defined by the imprint of global human activity. The term "anthropocene" [Greek "anthropo-" (human), and "-cene" (new)] was coined by ecologist Eugene Stoermer and popularized by chemist Paul Crutzen to emphasize the scale of the impact of human activity on the chemistry, biology, and geology of Earth's life support systems. Still to be determined, based on evidence about the human imprint on Earth's geology, is the appropriate time period for the beginning of the Anthropocene. Candidates include the beginnings of agriculture (~900 AD), the Nuclear Age (1950s), and the Industrial Revolution (~1750).

Tetrahedral chemistry education implies that students and teachers see how chemistry affects virtually every aspect of modern life – usually, but not always, for the better; that human activity is fundamentally altering our planetary boundaries; and that knowledge of chemistry is crucial in developing strategies to tackle global sustainability challenges.

1.4.3.1 Planetary Boundaries: A Chemistry Course Outline?

A series of seminal research publications, beginning in 2009, have set out to define and quantify the boundaries to our planet that should not be crossed, if humans are to prevent unacceptable human-induced global environmental change [27]. When reading, for the first time, the list of nine planetary boundaries (Figure 1.3) within which humans can safely operate, I was struck by the coherence between these boundaries and numerous underlying chemistry concepts presented to secondary and first-year post-secondary students. The list

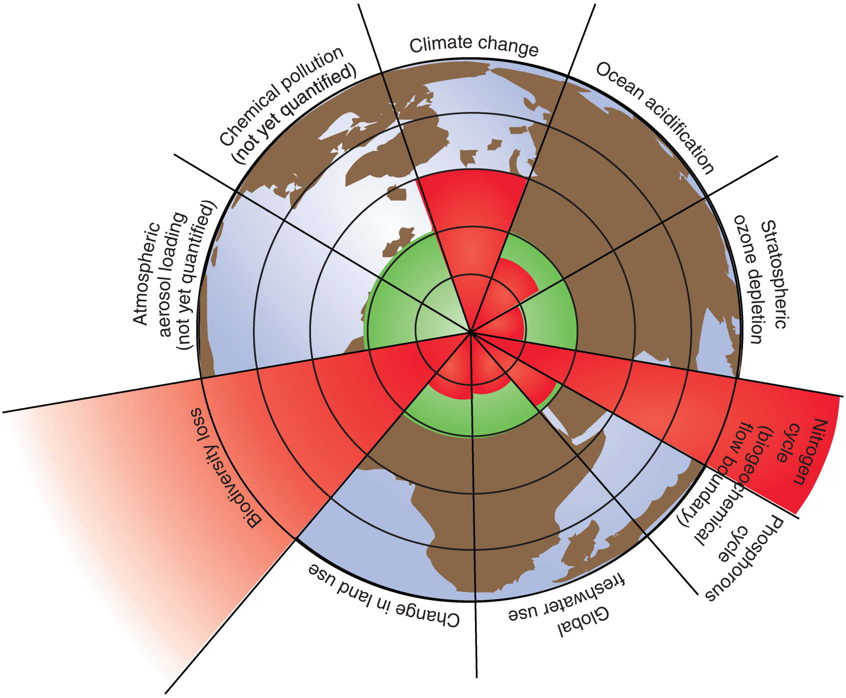


Figure 1.3 Illustration of the change to seven planetary boundaries from preindustrial levels to the present. The planetary boundaries attempt to quantify the limits within which humanity can safely operate without causing unacceptable global environmental change. (Photo credit: Azote Images/Stockholm Resilience Centre.)

of boundaries includes climate change, ocean acidification, interference with the nitrogen and phosphorus biogeochemical cycles, stratospheric ozone depletion, global freshwater use, changes in land use, atmospheric aerosol loading, rate of biodiversity loss, and (the poorly defined) chemical pollution.

Does secondary and post-secondary chemistry education, as currently practiced, reflect to any substantial effect our understanding of the fundamental role chemistry plays in altering Earth's boundaries? What are the implications of teaching students at more advanced levels who have learned, starting in elementary school, that we now live in the Anthropocene Epoch – defined in large part by changes to the chemistry of our lithosphere and atmosphere [28]?

> To master this huge shift, we must change the way we perceive ourselves and our role in the world. Students in school are still taught that we are living in the Holocene, an era that began roughly 12,000 years ago at the end of the last Ice Age. But teaching students that we are living in the Anthropocene … could be of great help. Rather than representing yet another sign of human hubris, this name change would stress the enormity of humanity's responsibility as stewards of the Earth. It would highlight the immense power of our intellect and our creativity, and the opportunities they offer for shaping the future.
>
> Nobel Laureate Chemist Paul Crutzen [29]

1.4.3.2 **Steps toward Anthropocene-Aware Chemistry Education**

A starting point in highlighting the intellect and creativity of chemists, and probing the opportunities chemistry offers for helping to shape the future (Crutzen, above), would be to correlate fundamental concepts in chemistry curriculum with those planetary boundaries where human activity is substantially impacting earth systems processes. Following this mapping activity, pedagogical strategies and curriculum that make these connections overt can be developed and implemented. Examples of such connections, listed in Table 1.1, are readily apparent upon even cursory examination, but seldom drawn out in core chemistry curriculum.

In the same way that an architect-educator (Section 1.4.1.1) might motivate students to develop the detailed understanding of the building blocks of architecture by introducing an elegant and complex building, the visual icon of our planetary boundaries could helpfully become one meaningful starting point and point of reference integrated throughout an introductory university chemistry course. The chemistry educator might motivate by starting, not with atoms, but with a view of the intricate and elegant chemical structures and processes that are found in every part of everyday life, including those that define our place in geological time. Keeping relevant human contexts in sight, students can then be guided through the details of structures, properties, and reactions of substances.

Table 1.1 Examples of relevant connections between six of the planetary boundaries and chemistry concepts.

Planetary boundary	Examples of underlying chemistry concepts
Climate change	Interaction of electromagnetic radiation with matter, infrared spectroscopy, thermochemistry, aerosols, isotopes, states of matter, combustion reactions, stoichiometry, hydrocarbons, and carbohydrates
Ocean acidification	Acid–base chemistry, equilibria, solubility, chemistry in and of water, chemical speciation, stoichiometry, and models
Stratospheric ozone depletion	Photochemistry, interaction of electromagnetic radiation with matter, ultraviolet spectroscopy, free-radical reactions, reaction mechanisms, thermochemistry, and kinetics
Nitrogen and phosphorus biogeochemical cycles	Main group chemistry, chemical speciation, stoichiometry, atom economy and atom efficiency, thermochemistry, and kinetics
Global freshwater use	Chemistry in and of water, chemical speciation, solubility and precipitation, equilibria, and states of matter
Atmospheric aerosol loading	States of matter and phase changes, thermochemistry, and acid–base chemistry

1.4.3.3 **Exemplars: Anthropocene-Aware Chemistry Education**

- The United Nations resolution declaring 2011 the International Year of Chemistry (IYC-2011) placed strong emphasis on the role chemistry plays in building a sustainable future [30]. During the year, educational and outreach activities focused on climate science, water resources [31], and energy gave further momentum to the link between chemistry and sustainability. One IYC-2011 legacy resource is a comprehensive set of free, interactive, critically reviewed, and Web-based learning tools to help students, teachers, science professionals, and the general public make sense of the underlying science of climate change. *www.explainingclimatechange.com* builds on and integrates connections to concepts in chemistry and physics, and is being used in chemistry and other courses at both the secondary and post-secondary level [32].
- National chemical societies have created programs and committees to raise the profile of chemistry education initiatives that address the human imprint on our planet. The Royal Society of Chemistry (RSC, UK) has teamed up with the ACS to form a sustainability alliance to help people understand the basic chemistry behind our global challenges and potential solutions. The ACS Committee on Environmental Improvement has instituted an annual award for exemplary incorporation of sustainability into Chemistry Education.
- As early as 1993, the ACS *Chemistry in Context* textbook for teaching chemistry to university students majoring in disciplines other than science has taught chemistry through real-world examples that engage students on multiple levels: their individual health and well-being, the health of their local communities, and the health of wider ecosystems that sustain life on Earth. Despite the success of this initiative, large inertia barriers have been experienced in extending similar approaches into courses for science majors.

1.5
Teaching and Learning from Rich Contexts

> … Now, for the first time in history, we are educating students for life in a world about which we know very little, except that it will be characterized by substantial and rapid change, and is likely to be more complex and uncertain than today's world … 'What kind of science education is appropriate as preparation for this unknown world?'
>
> Derek Hodson [33]

Are there approaches, whose effectiveness is supported by evidence, in which all three of these human activity dimensions to chemistry education (human activity of learning and teaching chemistry, human activity of carrying out chemistry, and Anthropocene-aware chemistry education) can be woven seamlessly into the practice of teaching and learning chemistry?

1.5.1
Diving into an Ocean of Concepts Related to Acid–Base Chemistry

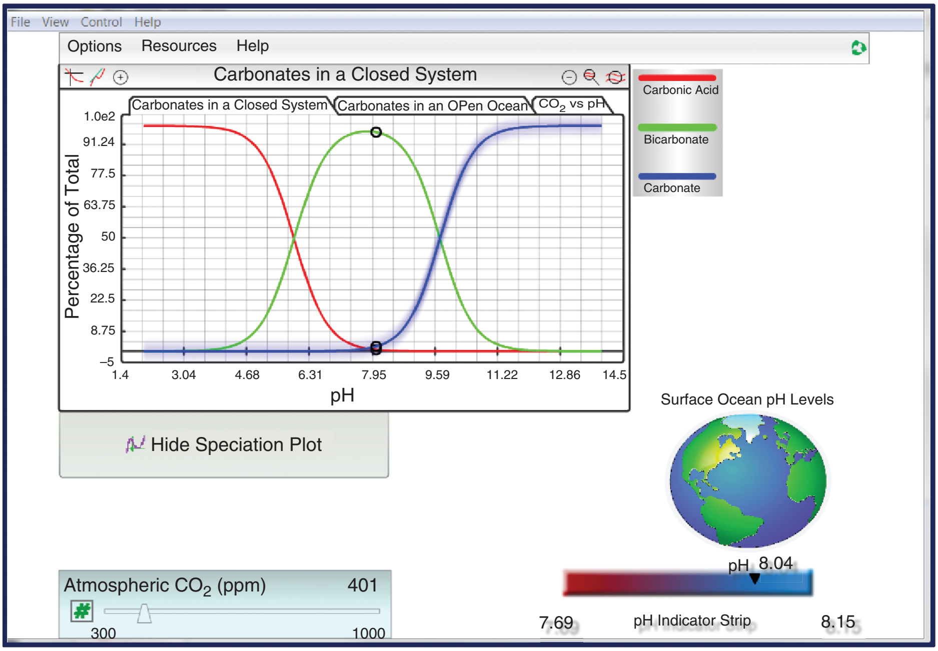
Consider an example of traditional "chemical" education curriculum that has seen little evolution over three or more decades. Almost every final-year secondary and first-year post-secondary chemistry course introduces a set of concepts that many students find challenging, and with a history of robust misconceptions, related to acid–base chemistry and solution equilibria and precipitation. Often taught as isolated concepts, these topics are introduced with a strong emphasis on the symbolic level of understanding. Coverage of these complex topics are highly mathematical, and algorithmic questions related to chemical equilibria, including acids and bases, feature prominently in classroom and standards exams. Yet, Yaron [34] reports that interviews with students only a few months after completing successfully a chemistry course with strong emphasis on acid–base equilibria, reveal that very little of the knowledge is retained. He suggests that a likely cause of this poor retention is that mathematical procedures related to equilibria are learned as procedures, with little connection to underlying concepts.

An alternative approach, which can incorporate all three dimensions of human activity described in Sections 1.4.1–1.4.3, is to introduce these core acid–base and equilibrium concepts through a compelling narrative, whose importance is or becomes evident to students. In VC3 (Section 1.4.1.5) [13] and in the learning resource *Chemistry: Human Activity, Chemical Reactivity* [21], we start with thought-questions that convey the urgency of the ocean acidification planetary boundary, rather than beginning with the detailed building blocks of knowledge related to mathematical and chemical reaction equations and chemical speciation. The conceptual building blocks are not neglected, but are carefully introduced *after* students understand both the importance of the global challenge and that they require knowledge about acids and bases and equilibria to make sense of the chemistry underlying the challenge to Earth's oceans.

Ocean acidification is one of the seven planetary boundaries that have been quantified [27b] with a global scale threshold. The 2009 analysis shows that Earth is approaching the proposed boundary of sustaining ≥80% of preindustrial aragonite mean surface seawater saturation state levels. About 70% of Earth is covered by oceans, and the oceans play a critical role in regulating earth's radiation balance, as well as providing habitat for more than a million species of plants and animals [35]. Mean ocean pH has already dropped from a preindustrial value of 8.2 to 8.1, and data on natural CO_2 seeps in tropical waters show that biodiversity of coral species is substantially diminished when ocean acidity increases [36]. While awareness is increasing of the damage to ocean coral reefs and other components of marine ecosystems from increasing hydronium ion concentration, little is generally known about another facet of the underlying chemistry – the dependence of speciation of dissolved CO_2 on pH. As pH drops, the speciation of carbon oxides from the initial dissolved CO_2 shifts significantly, with an increasing percentage of aquated hydrogen carbonate ions and lower availability of the aquated carbonate ions, which are particularly important in the formation of many marine exoskeletons.

In developing this approach to introducing acid–base chemistry and solution equilibria and precipitation, the VC3 research team started with a review of research literature of prior knowledge and documented student misconceptions related to the chemical concepts. Learning objectives were then developed to address core concepts related to the chemistry of acids and bases and equilibria, as well as the principles of climate literacy related to the role of the oceans. Learning objectives included not only what students should know about particular concepts but also what the evidence for that knowledge is, and the climate contexts that are related to those concepts. A set of interactive Web-based lessons were then created, based on effective practices for the creation of electronic simulations [37]. Integrated throughout the lessons are new digital learning objects, such as one that invites students to interrogate the ocean system with a model that correlates atmospheric CO_2 with surface ocean pH, and the relationship between pH and speciation of carbonic acid, bicarbonate, and carbonate ions (Figure 1.4). To provide evidence about the effectiveness of this approach, an assessment of learning gains of chemistry concepts related to acid–base chemistry and relevant climate science concepts is being carried out, comparing students using the VC3 resources with control groups using conventional approaches.

It can readily be seen how each of the three dimensions of human activity described in Sections 1.4.1–1.4.3 is emphasized in this approach, with careful implementation. (i) *The human activity of learning and teaching chemistry.* Materials are developed after consideration of student conceptions and documented student misconceptions to achieve both lower and higher order learning objectives. A story is used to introduce an important set of concepts through interactive learning tools that probe student understanding, provide feedback, and encourage deep and active learning. Evidence about the effectiveness of



Atmospheric CO_2 (ppm) 401

pH 8.04

Figure 1.4 Screen capture from interactive digital learning object that models the correlations between atmospheric CO_2 and ocean pH, as well as the speciation of carbon in the ocean. (Figure courtesy of the King's Centre for Visualization in Science.) (*www.kcvs.ca*).

the approach in achieving learning gains is obtained. (ii) *The human activity of carrying out chemistry.* The nature of scientific evidence as well as the application of conceptual and mathematical models to analyze data and explain observations is demonstrated, and students are introduced to complexity in a contemporary scientific global challenge. Complexity is a feature of the nature of science that is often given insufficient attention in conventional approaches. (iii) *The human activity that has imprinted itself in such a substantial way on the chemistry of our planet that it has defined a new geological epoch.* Chemistry students learn about ocean acidification, one of the planetary boundaries where human-induced global environmental change is becoming increasingly evident on a relatively short time scale.

1.5.2
What Is Teaching and Learning from Rich Contexts?

Introducing acid–base chemistry and solution equilibria through ocean acidification is an example of an approach we describe as *teaching from a rich context*, and that has potential to effectively model science education as preparation for the complexity and uncertainty of our world (Hodson, Section 1.5). Context-based approaches, which are also considered by Parchmann in Chapter 10 of this title [38], have been described as "approach(es) adopted in science teaching where context and applications of science are used as the starting point for the development of scientific ideas. This contrasts with more traditional approaches that cover scientific ideas first, before looking at applications [39].” Through the context, students are expected to give meaning to the chemical concepts they learn [40]. The learning theory concept of situated cognition provides one theoretical framework for using contexts to scaffold the development of chemical concepts [41]. Situated cognition assumes that learning is embedded in social, cultural, and physical contexts [42], and when meaningful contexts are used to introduce concepts, content will be more firmly anchored in memory and more easily applied to new contexts. Meaningful learning occurs when incoming information can be linked to and interpreted by what the learner already knows or by what comes to have meaning for him/her [41].

Context-based learning shares features and aspects of historical evolution with other approaches, such as case studies, problem-based learning, and Science–Technology–Society (STS) [43] and Science–Technology–Society–Environment (STSE) teaching. DeJong [44] identifies four common domains for contexts: the personal, social and societal, professional practice, and scientific and technological domains. He traces the evolution of the use of contexts to teach chemistry from initiatives in the 1980s such as ChemCom and Chemistry in Context in the United States, Salters Chemistry in the United Kingdom, Chemie in Kontext in Germany, and Chemistry in Practice in the Netherlands. He suggests that in some of the most recent and effective implementation of contextual learning, contexts initially precede concepts, providing both an orienting function and increasing motivation for learning new concepts. In some cases, a follow-up inquiry context is used to help students see the need to apply their knowledge to new situations. We propose that the term “rich context” appropriately applies to implementation that provides deep and rich opportunities for learning concepts through contexts and applying that knowledge to new contexts.

Using insights from linguistics and learning theories, Gilbert [5] suggests ways in which context-based approaches have the potential to address the five challenges of chemical education identified in Section 1.4.1 (content overload, numerous isolated facts, difficulty in transferring learning to problems presented in different ways, lack of relevance of knowledge to everyday life, and too much emphasis on preparation for further study in chemistry). Pilot and Bulte [45] analyze significant new initiatives to develop context-based approaches to chemistry curriculum in five different countries, and describe ways in which each initiative has contributed to the five challenges listed above. They also identify the importance of assessment for context-based chemistry education that is coherent with the learning goals, approaches, and vision of the approaches.

1.5.3

Teaching and Learning from Rich Contexts – Evidence for Effectiveness

Several challenges become apparent when seeking to obtain research evidence about the effectiveness of context-based approaches relative to long-standing practices of "chemical" education. One challenge is a common understanding of key terms – all learning occurs within multiple contexts – the system contexts of a classroom and curriculum, the socio-cultural context for learning, and the internalized context – and practitioners use the term "context" in diverse ways. Context-based approaches also have a wide range of goals and approaches, and they are implemented across a range of educational levels to both science and non-science majors, and in very diverse school cultures. It can be difficult to measure gains from any learning intervention when learning outside of formal curriculum dominates [46]. However, evidence for effectiveness of context-based learning is emerging from assessment [45] of implementations such as the five international approaches described in Section 1.5.2, and several recent large-scale reviews converge on some important conclusions, while pointing the way toward areas where further research is needed. Bennett *et al.* [39] presents a synthesis of the research evidence from 17 experimental studies in eight countries on the effects of context-based and STS approaches. This work draws on the findings of two systematic reviews of the research literature, including a previous survey of 220 context-based and conventional approaches [47]. Overton [41] gives an overview of both context-based approaches and problem-based learning in both chemistry and physics, and Ültay and Çalik [46] has recently reviewed 34 context-based chemistry studies.

Perhaps the most important finding from this review of assessments of implementations is that context-based learning results in positive effects on attitudes. Students using context-based curricula view chemistry as more motivating, interesting, and relevant to their lives [46, 47]. Students develop a range of transferrable and intellectual skills [41], including higher order thinking skills. Conclusions about the important question of gains in student's understanding/cognition are more tenuous, as relatively few well-designed, comparative studies have been done with different contemporary learning models. Bennett's systematic review of experimental studies [39], using methods from the UK Evidence, Policy, and Practice Initiative, concludes (from 12 studies considered medium to high quality) that the understanding of scientific ideas through context-based approaches is comparable to that of conventional approaches. Bennett concludes that "reliable and valid evidence is available to support the use of contexts as a starting point in science teaching: there are no drawbacks in the development of understanding of science, and considerable benefits in terms of attitudes to 'school' science [39]."

1.5.4
From "Chemical" to "Chemistry" Education – Barriers to Change

Educational change from "chemical" toward more tetrahedrally shaped "chemistry" education pre-requires both a vision for identifying and meeting the learning needs of students in diverse cultural and educational settings, and a critical mass of professional educators willing to step back from historical practices to examine evidence for what works and what doesn't in current practice.

Necessary also are a keen awareness of inertia and other barriers to change, along with healthy doses of both time and patience. Communities of learning and professional practice which place high priority on effective practices for learning and teaching need to support and guide innovators and galvanize others into examining and trying out more effective approaches. Finally, a commitment to an on-going process of assessment to provide evidence for the effectiveness of new approaches is needed, and a willingness of proponents of educational reform to dynamically adapt new approaches in response to that evidence.

Professional development to support chemistry educators is crucial. Stolk has recently carried out iterative empirical studies in which a professional development framework to empower chemistry teachers for context-based education is designed, implemented, and evaluated [48]. Building on Stolk's three-phase framework (preparation to teach context-based units, instruction, and reflection and evaluation), Dolfing [49] reports on four empirical studies to better understand what strategies within a professional development program are needed to support teachers in developing domain-specific expertise in teaching context-based chemistry education.

Effective teaching of chemistry does not develop in the abstract. It needs to be grounded in the discipline of chemistry and in the many interfaces where chemistry is practiced. So, in addition to actions of individuals, communities of learning, and professional teacher development programs, disciplinary scientific societies also have an important role to play. Recognizing that most STEM faculty at the post-secondary level begin their careers with little or no professional training in teaching and little or no knowledge about effective teaching practices, a collaborative initiative of the U.S. Council of Scientific Society Presidents and other partners have produced a report [50] on the importance of disciplinary societies in stimulating and supporting faculty to implement successful teaching strategies. The report highlights effective practices which include new faculty workshops, annual disciplinary teaching workshops and education sessions, teaching fellowships, teaching institutes, and other strategies for professional development to facilitate more widespread change in STEM learning and teaching.

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