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Infusing Sustainability Science Literacy through Chemistry Education: Climate Science as a Rich Context for Learning Chemistry

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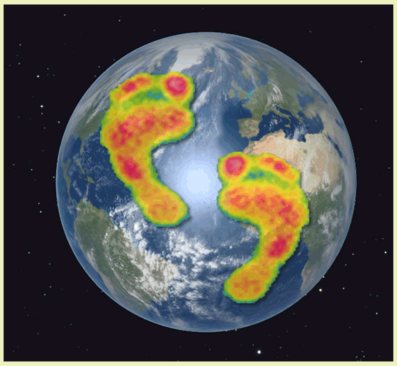

ABSTRACT: Global science is paying increasingly urgent attention to sustainability challenges, as evidenced by initiatives such as the working group determining whether Earth has moved from the Holocene to the Anthropocene Epoch on the geologic time scale and the interdisciplinary efforts to define and quantify our planetary boundaries. Despite the fact that much of the scientific work underlying these initiatives is based on measurements of fundamental chemistry parameters, sustainability literacy has not been incorporated in any systematic way into the undergraduate chemistry curriculum. We report here on the philosophy and implementation of a NSF-funded initiative, Visualizing the Chemistry of Climate Change (VC3), which provides an exemplar for developing strategies to fill that gap, focusing on climate change, one of the defining sustainability challenges of the 21st century. VC3 targets the strategic first year university and college chemistry courses that are common to the program requirements of many science and engineering majors. The overall goals of the VC3 project are to infuse climate literacy principles into the learning of representative core topics in North American general chemistry courses for science majors, while demonstrating that learning core chemistry topics by starting with an important rich context is a viable approach.

KEYWORDS: *Climate change, Sustainability, Education, Rich context, General chemistry, Climate literacy, Sustainability science literacy*

> *"The crisis of sustainability, the fit between humanity and its habitat, is manifest in varying ways and degrees everywhere on Earth. It is not only a permanent feature on the public agenda; for all practical purposes it is the agenda··· Sustainability is about the terms and conditions of human survival, and yet we still educate at all levels as if no such crisis existed. . ."*[1]

David Orr's assessment of education for sustainability was made 22 years ago, at about the time when most 2014 university graduates were just joining 5.5 billion other human beings on Earth. During the two decades since those university graduates were born, the strain on our planet's life support systems by the activity of now 7.2 billion humans has become increasingly clear. Our human footprint is measured, in part, through changes to fundamental chemical parameters of the lithosphere, cryosphere, hydrosphere, biosphere, and atmosphere. For example, the annual inputs of reactive nitrogen to the atmosphere from anthropogenic activity now exceed that from natural sources. Over the 22 years, those university graduates have been on Earth, atmospheric CO_2 levels have increased from 355 to over 400 ppm and average global sea surface temperature has increased by about 0.3 °F. The extent to which these shifting chemical parameters are presented to our graduates via traditional chemistry (or other) university courses will profoundly affect their understanding and appreciation of global science initiatives that define and place sustainability challenges on the public agenda. Two examples of high profile interrelated initiatives that are guiding scientific and public sustainability discourse are as follows:

The Anthropocene Epoch. An International Union of Geological Sciences blue-ribbon working group of the Subcommission on Quaternary Stratigraphy is expected to report by 2016 on whether sufficient scientific evidence is present to formally determine that we have already moved from the relatively stable interglacial Holocene Epoch to the Anthropocene Epoch (Greek "anthropo-" (human), and "-cene" (new)), on the geologic time scale.[2,3] One of the implications of formally renaming our planet's place in geologic

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time would be to raise awareness in other scientific communities and the public of the scale of the human footprint on Earth's life support systems. Future civilizations would look back at this boundary and see clearly that chemical and other parameters of our planet were fundamentally and measurably transformed by human activity as the new Anthropocene Epoch began.[4]

Planetary Boundaries. Interconnected with the proposed formalization of the Anthropocene are interdisciplinary research initiatives to define and quantify "planetary boundaries," the state of earth system parameters that define a safe operating space for humanity.[5,6] Measurement of changes to chemical parameters are central to the definition and quantification of the nine proposed planetary boundaries, including the levels of stratospheric ozone, concentration of atmospheric carbon dioxide, global mean saturation state of aragonite in surface seawater, amount of anthropogenic nitrogen removed from the atmosphere, amount of anthropogenic phosphorus deposited in the oceans, and overall atmospheric particulate (aerosol) concentration.

The molecular sciences, at their interfaces with earth and life sciences, are central to these global science sustainability efforts, and the chemistry profession is grappling with its key role in understanding and working toward solutions to these challenges. The National Research Council of the U.S. National Academies undertook an initiative to articulate the grand challenges for the chemical sciences in the 21st century a decade ago.[7] Many of these chemistry grand challenges are linked directly or indirectly to important sustainability considerations, such as in the NRC report on identification of challenges for chemistry in the areas of atmospheric and environmental chemistry and energy. In a separate 2003 NRC initiative to assist the "chemical industry" in its broadest sense to achieve sustainability goals, the "grand challenge" of sustainability science literacy was set out, to... "*improve sustainability science literacy at every level of society—from informal education of consumers, citizens, and future scientists, to the practitioners of the field, and the businesses that use and sell these products.*"[8] The 2003 NRC report describes literacy in sustainability science as bringing together "scholarship and practice, global and local perspectives from north and south, and disciplines across the natural and social sciences, engineering, and medicine,"[8] and suggests that greater sustainability science literacy will be required for industry to move toward more sustainable practices. If recent university graduates were to reflect on their own education in and about chemistry, would they concur with Orr's assessment? Or would they have experienced sustainability literacy deeply connected to their learning of fundamental concepts of chemistry, as envisioned, perhaps by the NRC report?

Our assessment is that, despite the central role that the chemical sciences play in understanding earth system parameters, little has been done since Orr's assessment to systematically address the disconnect that persists between global initiatives to address sustainability issues related to chemistry and the research and practice of chemistry educators at all levels. Important steps are just beginning to be taken in formal science education contexts. One such step is the U.S. Next Generation Science Standards (NGSS).[9] As they are implemented over time, these standards will emphasize sustainability literacy in various ways at the K−12 level. This should, in due course, lay the groundwork in the United States for fuller integration of sustainability science literacy into undergraduate chemistry curricula.

We report here on the philosophy and implementation of an initiative, Visualizing the Chemistry of Climate Change (VC3), which may serve as an exemplar for developing strategies to fill the gap that is present at the undergraduate level.

■ THE SUSTAINABILITY SCIENCE LITERACY CHALLENGE

A strategic place to begin in addressing the sustainability literacy challenge set out by Orr and the NRC report is in first year chemistry courses taught at universities and colleges. One or more courses in chemistry at the post-secondary level are a common thread in program requirements designed to prepare future chemists, life scientists, engineers, physical scientists, and others for professional careers and for life as citizens in the 21st century. However, little systematic attention has been given by chemistry educators to equipping students in these gateway chemistry courses for science majors to connect the chemistry content they are learning with any number of challenges faced by society, including fundamental sustainability topics.[10] Textbooks, learning resources, and learning objectives for introductory university and college chemistry courses for science and engineering majors infrequently foreground sustainability challenges or integrate sustainability science concepts into the student experience of mastering chemistry, and chemistry educators find few resources in the leading journals in chemistry education to support them in developing approaches to help students make meaningful connections.[11] In parallel with initiatives in chemistry to highlight the importance of sustainability as an integrative theme in research, we challenge the chemistry education profession to envision a substantive and visible role in infusing sustainability science through chemistry curriculum, so as to prepare 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...*"[12]

One example of a global sustainability challenge that defines the 21st century is climate change. The 2013 release of the fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the 2014 U.S. National Climate Assessment (NCA), and proposed U.S. Environmental Protection Agency regulations mandating 30% reductions in carbon emissions from coal-fired power plants have dominated print and media headlines. The latest NCA Assessment concludes that "*human activities are now the dominant agents of change*", and "*the evidence of human-induced climate change continues to strengthen and that impacts are increasing across the United States.*"[13]

Achieving climate science literacy requires at least some level of understanding of the chemistry underlying climate topics such as the differences and connections between ozone depletion and global warming, definition of a greenhouse gas, radiative forcing and global warming potentials of different greenhouse gases, how substances interact with electromagnetic radiation in different regions of Earth's atmosphere, speciation of carbon in the ocean and ocean acidification, isotopic ratio proxy measurements of temperature, earth's radiation balance, combustion reactions, formation and dispersion of aerosols, and positive and negative feedback loops involving water and other substances.

Despite both the widespread articulation and dissemination of climate science literacy goals and the inherent connection to chemical concepts and parameters, post-secondary chemistry students, including those majoring in chemistry, receive relatively little support in connecting the chemistry they learn to this global sustainability challenge. This lack of attention to climate science is not uniquely a chemistry education or a post-secondary education challenge. Analysts have concluded that climate change science, with its complex links to both natural processes and human activity, has fallen into a systemic hole in the science education system.[14] To take the first steps to address this, the 2013 U.S. NGSS now include global climate change as one of four sub-ideas in the core idea of Earth and Human Activity at both the middle school and high school levels.[15] Upon implementation of NGSS, students coming into post-secondary science classrooms in the United States should bring heightened awareness of our planet's place in geologic time and that understanding chemical parameters is fundamentally important to meaningfully address sustainability challenges such as climate change. Many of those students pursuing careers in science and engineering are required to take at least an introductory chemistry course. Given the centrality of chemistry at its interfaces with physics, biology, and the earth sciences that underlies so many aspects of climate science, chemistry education has a unique and compelling opportunity to play a meaningful role in contributing to climate science literacy by university and college graduates, and a strategic place to start is with general chemistry courses.

■ THE CHEMISTRY EDUCATION CHALLENGE

In parallel with chemistry-related global sustainability science literacy opportunities, chemistry education faces its own grand challenges related to both pedagogy and curriculum. A review of the interrelated problems facing global secondary and post-secondary chemistry education highlights that students experience the following: content overload, presentation of 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 rather than for development of scientific literacy.[16,17]

Introductory university and college chemistry courses for science and engineering majors have become the focus of particular attention in addressing chemistry education's challenges and in implementing diverse strategies for reform. In North America, such foundational courses play a central role, giving students with interests in health sciences, engineering, materials, and physical sciences, as well as chemistry, a formative introduction to the discipline. For most of these science students, introductory (general) chemistry courses, and perhaps a course or two in organic chemistry, are the only introduction to the discipline of chemistry that they will receive. Yet the reality is that many students taking chemistry find the discipline irrelevant, uninteresting, and indigestible, and they progress in their attitudes of chemistry throughout secondary school and general chemistry, from "*I can't understand*" to "*I shall never understand*," and finally to "*I don't care if I understand*."[18]

The extent of dissatisfaction with student experiences varies widely, reflecting the great diversity in the structure and delivery of chemistry courses in different school and university systems and in different cultures and countries. Some common themes emerge, however, in articulating key reasons for negative student experiences of first year chemistry. These include insufficient attention by educators to identifying the student audience and their diverse needs for learning chemistry, lack of clearly articulated student learning outcomes, over-reliance on teacher-centered lecture-based pedagogies,[19] over-emphasis on the mathematical and quantitative aspects of chemistry, insufficient activities and assessment at higher levels of cognitive taxonomies, and excessive demands on student working memory.[20−22]

As a result of its position in the curriculum for so many science and engineering majors, general chemistry courses provide a unique opportunity to demonstrate the power of the tools of chemistry and their application to societal issues, including sustainability challenges. How can chemistry educators leverage this opportunity?

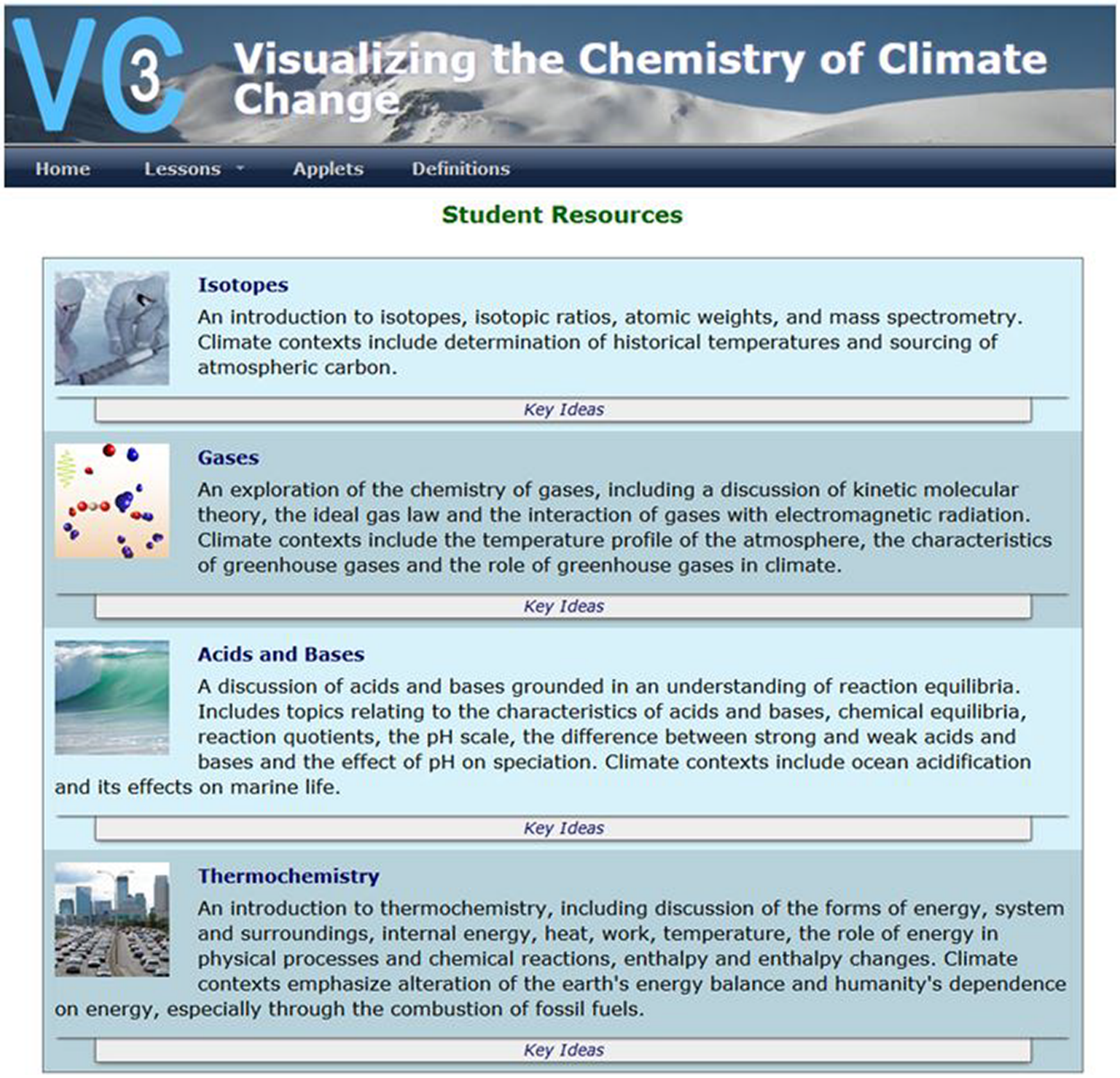
■ TACKLING THE DUAL CHALLENGES OF SUSTAINABILITY SCIENCE LITERACY AND CHEMISTRY EDUCATION BY TEACHING AND LEARNING FROM RICH CONTEXTS

The community of chemistry education research and practice is giving priority to addressing the educational challenges identified above. Examples of approaches gaining traction have recently been summarized.[23] They include facilitating student learning *in*, *about*, and *through* chemistry by (a) changing the emphasis from teaching to student learning, (b) understanding student prior conceptual understanding and developing validated inventories and strategies to identify and address misconceptions, (c) using models for learning that account for different learning styles and limits to cognitive load, (d) engaging students with active and collaborative learning, (e) motivating students by developing curriculum that connects to the lived experience of students and societal needs, (f) implementing strategies for faculty professional development, and (g) integrating into education the responsible and ethical practice of science.

One approach, in particular, has considerable potential to concurrently address the dual challenges of addressing sustainability science literacy goals and making chemistry education more relevant to the diverse group of students taking introductory chemistry courses. Context-based learning uses a motivating context or application of science as the starting point to develop scientific content for students rather than the more traditional approach of systematically building up general chemistry concepts and then introducing applications of those ideas. Related to and often integrated into context-based learning are strategies such as problem-based learning, teaching science through case studies, and science−technology−society (STS) approaches. The American Chemical Society has successfully used context-based learning for decades in its Chemistry in Context resources for chemistry students in nonscience majors courses,[24] but few attempts have been made to introduce science majors rigorously to chemistry through motivating and societally important contexts.

For any educational reform initiative to take hold, evidence for effectiveness is needed. Several large-scale reviews of context-based learning at secondary and post-secondary levels, which is more widely adopted in Europe, conclude that context-based learning results in positive effects on student attitudes. Students view chemistry as more motivating, interesting, and relevant to their lives and develop a range of transferrable higher order thinking skills, with at least no apparent drawbacks in their understanding of scientific ideas.[23]

As an exemplar for how sustainability science literacy could be incorporated into the general chemistry curriculum, we



Visualizing the Chemistry of Climate Change

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. Opening page for student resources from Visualizing the Chemistry of Climate Change interactive Web materials (www.vc3chem.com). Figure reproduced with permission of the King's Centre for Visualization in Science (www.kcvs.ca).

report an initiative with the goal of teaching students key topics in general chemistry, starting with the rich context of climate change, and assessing student learning gains both in the chemistry content and the climate science context. We use the term "*teaching from a rich context*" to describe learning that provides rich opportunities to master content topics, motivated by making sense of an important and engaging context.

INTRODUCING GENERAL CHEMISTRY TOPICS THROUGH RICH CONTEXTS: VISUALIZING THE CHEMISTRY OF CLIMATE CHANGE

Visualizing the Chemistry of Climate Change (VC3, Figure 1) is a NSF-funded project that has brought into partnership the American Chemical Society and a team of North American chemists, physicists, chemistry education researchers, and scientific visualization experts, including an interdisciplinary team of undergraduate students. The two overarching goals of the project are to (a) infuse climate literacy principles into the learning of representative core topics in North American general chemistry courses, while (b) demonstrating that learning core chemistry topics by starting with an important rich context is a viable approach to teaching science majors.

The VC3 interactive Web resources are intended to support student learning in general chemistry classes as a supplement to the textbook, and they lend themselves particularly well to providing the robust, interactive, peer-reviewed resources needed to support active learning pedagogical approaches such as required in blended learning environments.

VC3 CHEMISTRY TOPICS AND CLIMATE CONCEPT QUESTIONS

Four major chemistry topics were selected, based on the design principles described in the next section: isotopes, gases, acids and bases, and thermochemistry. Each chemistry topic was introduced with an overarching climate concept question, as follows:

Isotopes Climate Context Question *— How is 800,000 years of temperature data determined from ice core samples?*

For students to understand how proxy measurements of Earth's temperature are obtained, they need to be introduced to the variation in isotopic ratios of water molecules in Antarctic ice cores. This, in turn, requires an understanding of the nature of isotopes, the difference between heavy and light water, and the temperature dependence of the fractionation that occurs

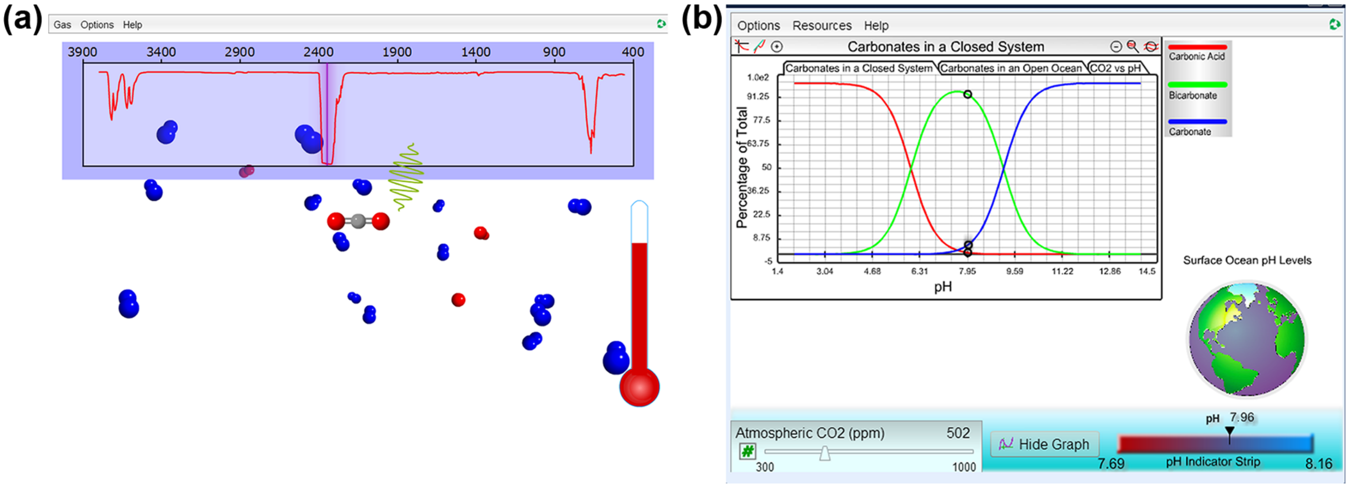


Figure 2. Interactive applets from Visualizing the Chemistry of Climate Change showing (a) molecular-level understanding of tropospheric warming via collisional de-excitation of greenhouse gases and (b) carbon speciation with ocean acidification (www.vc3chem.com). Figures reproduced with permission of the King's Centre for Visualization in Science (www.kcvs.ca).

during cycles of evaporation and condensation. This climate-rich context question leads naturally into discussions of isotopic ratios and atomic weights, and the evidence for atomic weights in mass spectrometry. The climate question also provides a helpful context for explaining why the new IUPAC atomic weights for certain important elements are no longer expressed as single numbers but as intervals. Atomic weights for these elements are not considered constants of nature but vary from sample to sample as a result of biochemical pathways and environmental and climatic conditions

Gases Climate Context Question *— Which atmospheric gases support life directly? Which gases support life by regulating the energy balance of our planet?*

Often the treatment of gases in general chemistry courses emphasizes, almost exclusively, the similarity among thermodynamic properties of many gases under certain conditions (the ideal gas law). The climate context makes it possible for instructors to balance this emphasis with an understanding of what also makes atmospheric gases different from each other. At the heart of these differences is the absorption of electromagnetic radiation by substances, particularly in the infrared region of the spectrum. The evidence for these differences is obtained from IR spectroscopy. This leads naturally to a discussion of structure–activity relationships that determine whether molecules of a particular substance will be greenhouse gases. An interactive simulation is used to present a molecular-level understanding of how greenhouse gases contribute to tropospheric warming (Figure 2a).

Acids and Bases Climate Context Question *— How can chemistry explain the effects of increasing levels of atmospheric carbon dioxide on the pH of the ocean? What are other effects on marine life?*

Studies have shown that many students do not remember details of chemistry related to acid/base chemistry and solubility and precipitation and complexation shortly after completing general chemistry. This may be because mathematical procedures related to equilibria are learned as procedures, with little connection to underlying concepts.[21] Ocean acidification provides a motivating and integrative context to introduce interconnected fundamental concepts related to acid and base strength, pH dependence of speciation in aqueous solutions (Figure 2b), and the importance of understanding solubility and precipitation.

Thermochemistry Climate Context Question *— How is the way we power our planet altering the earth's energy balance?*

Key concepts related to energy transfer, heat and work, energy and phase changes, and energy and chemical reactions can all be used to form the basis for a more in-depth understanding of the implications of the energy choices we make. The research literature suggests that students have a very difficult time connecting the symbolic and mathematical representations of thermochemistry with macroscopic observations and molecular-level explanations.[25] Thermal infrared imaging was exploited in the creation of these resources to help students "see" phenomena related to heat transfer, phase changes, and energy changes in chemical reactions.

■ EXEMPLARY VC3 DESIGN FEATURES WITH POTENTIAL TO INFORM OTHER INITIATIVES

The VC3 team worked from design principles that proved to be important in guiding the production and testing of resources and in assessing their effectiveness. We believe that the VC3 approach and features described below introduce general chemistry topics to science majors through climate science-rich contexts and may serve to inform other initiatives that use rich contexts, including sustainability challenges, to introduce chemistry.

(1) The choice of chemistry content and sustainability contexts was based on mapping the core chemistry concepts covered in standard courses with widely accepted climate literacy principles, most of which drew on an understanding of chemistry. This mapping was achieved by carrying out a survey of leading textbooks and representative course outlines for general chemistry courses at North American universities and colleges to identify the core chemistry content areas or major units common to most courses. In parallel, it was determined that an appropriate threshold set of climate literacy principles was the seven essential principles of climate science, developed by a community effort of climate scientists, educators, and representatives of United States agencies under the umbrella of the U.S. Global Change Research Program.[26] A detailed analysis identified subtopics of the seven major chemistry content topics that would best lend themselves to making

connections to the climate literacy principles. A visual map was developed to highlight the cross-correlations between the core chemistry topics and the seven essential climate principles. This mapping exercise identified the four priority chemistry topics listed above that showed considerable promise for motivating students and connecting sustainability and chemistry.

(2) Misconceptions about both climate science and chemistry content were documented and learning resources created with an overt awareness about the prior conceptual understanding of students.

(3) On the basis of the mapping exercise and inventory of known student misconceptions, chemistry and climate literacy learning objectives were written for the four priority chemistry topic areas listed above. Each content learning objective (What do we know?) was accompanied by an evidential learning objective (How do we know this?) and a contextual objective (Why should we care?).

(4) Design principles for Web-based materials emphasized that they be engaging and interactive, based on effective practices for visualizations,[27] and that they support active learning pedagogies that STEM education research shows contribute to student success.

(5) Appropriate evaluation and assessment was needed to ensure the robustness and scientific credibility of the learning resources and their alignment with the learning objectives.

■ SUMMARY AND NEXT STEPS

Visualizing the Chemistry of Climate Change is an exemplar that invites the scientific community with an interest in sustainability and the education community seeking to enrich student learning to come together to identify the opportunities and challenges in infusing sustainability science literacy into chemistry education. While the materials should serve a range of undergraduate science courses, the project specifically targets the strategic first year university and college chemistry courses that are common to the program requirements of many science and engineering majors. VC3 also provides a model to test the use of a motivating rich context to enrich the teaching and learning environment in general chemistry courses. Lessons learned from the project will help to identify the activation barriers that need to be overcome for more widespread incorporation of sustainability science literacy goals into undergraduate science curricula and for new pedagogical approaches to take hold in science classes.

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Notes

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