Chemistry Education: Ten Facets To Shape Us

Vicente Talanquer*
Department of Chemistry and Biochemistry, University of Arizona, Tucson, Arizona 85721, United States

ABSTRACT: The chemistry knowledge that we want our students to develop is rich, complex, and multifaceted. However, some teachers and instructors at the secondary school and college levels approach it in rather rigid and unidimensional ways. The central goal of this contribution is to describe and discuss 10 different complementary perspectives or "facets" from which chemistry content in introductory courses can be analyzed. This multidimensional view may help chemical educators, particularly those who are new to the profession, enrich their understanding of chemistry as a teaching subject and open the path for diverse re-conceptualizations of the chemistry curriculum.

KEYWORDS: General Public, Curriculum, Enrichment/Review Materials, Chemical Education Research
FEATURE: Chemical Education Research

INTRODUCTION

Chemical education research in the past 40 years has shown that many students completing introductory chemistry courses at the secondary school and college levels do not develop the meaningful understandings that we value.1–3 These results have prompted some chemical educators to suggest, design, and implement different approaches to the conceptualization and teaching of school chemistry, particularly at the high school and first-year college levels.4,5 Unfortunately, the impact of such reform efforts has been limited, in many cases circumscribed to the schools, colleges, and universities in which those innovative chemical educators reside. Despite existing evidence about the limited efficacy of conventional chemistry courses, the calls for change made by a variety of chemical educators6,7 have not translated into collective action.

There may be several reasons for the limited, or rather slow pace of change in chemistry education. It is possible that existing evidence about our educational problems is judged to be invalid, unreliable, or not extensive enough to merit attention by many teachers and instructors. It may be that the evidence has not been disseminated widely among chemical educators. Perhaps educators’ strong personal beliefs about teaching and learning make them dismiss evidence that contradicts their expectations. Even if educators accept the existing evidence, they may not be convinced that alternative teaching approaches will yield better results. Additionally, many secondary school teachers and college instructors may not have the knowledge and skills that would be needed to approach chemistry teaching in different ways, and if they do, they may not have the time or the proper incentives to implement the suggested changes.

Among the various reasons that may lie behind the prevalence and persistence of ineffective approaches to the teaching of chemistry at different educational levels, I would like to highlight one that I see as a major contributor to the problem; one that I face regularly as a chemistry teacher educator. Many young, as well as some experienced, chemistry teachers seem to hold a monofaceted and unproblematic view of the subject matter they teach. These educators believe that the central challenge in teaching chemistry is identifying the best activities to engage students with prescribed textbook content, rarely questioning or critically analyzing the subject matter. Unfortunately, this lack of reflection on the content to be taught tends to thwart the most creative teaching plans.

Most prospective secondary school teachers with whom I work, as well as some high school chemistry teachers and college general chemistry instructors with whom I have interacted, tend to think of the content of introductory chemistry courses as a collection of well-set topics. Examples include stoichiometry, atomic structure, periodicity, and chemical bonding. The extent to which these educators recognize underlying themes or meaningful connections between these topics depends largely on their own understanding of the subject matter and their experience working in the chemistry classroom. However, in general, even those instructors with the strongest content background or the most teaching experience rarely go beyond describing chemistry knowledge as organized in the broad categories commonly presented in the table of contents of conventional general chemistry textbooks (see Table 1).

Given these constrained views of chemistry knowledge, I would suggest that a significant strategy for change in chemistry education, particularly in introductory general chemistry courses at the high school and college levels, would be to focus on enriching and diversifying the ways in which chemistry teachers and instructors think about the content that they teach. Recent work in...
In curriculum design, the term “big idea” traditionally refers to a statement that summarizes core knowledge in a discipline that we would like students to understand. For example, the statement “all matter is particulate in nature” may be considered a big idea in chemistry. Although the notion of organizing science curricula around big ideas has been around for over 20 years, many prospective and novice teachers have serious difficulties identifying big ideas in their area of interest. When asked to state a big idea in chemistry that their students should understand, many of my prospective chemistry teachers say things like “they need to know about bonds”, or “they need to understand chemical reactions”, instead of clearly expressing the specific enduring understandings that they want students to develop.

Coming up with big ideas in chemistry, or even a subfield of our discipline, is not an easy task, particularly when one has never been exposed to or asked to think about them. However, there are insightful works that can be used to initiate discussions and reflections about chemistry content from a “big ideas” perspective. For example, Ronald Gillespie11 and Peter Atkins,12 two well-known and respected chemistry educators, have independently identified and discussed what they consider big ideas in the discipline (see Table 2). More recently, the College Board has published a set of standards for college success that includes a collection of enduring understandings that nicely summarize big ideas for introductory chemistry courses at the secondary school and college levels.13 Similar ideas can be found in the recent National Research Council (NRC) Framework for K–12 Science Education14 and the anchoring concepts content maps developed by the ACS Examinations Institute.15,16

Asking teachers to critically analyze these types of documents could shift their attention from the topics to be covered in a chemistry course to the big ideas students should develop. It could also help chemistry teachers build more meaningful connections between different concepts in the chemistry curriculum. Teachers and instructors could also benefit from reviewing examples of curriculum projects for introductory chemistry that have explicitly used big ideas as organizing principles. That is the case of the Chemistry X11 curriculum15 and the Chemistry, Life, the Universe and Everything (CLUE) project18 at the college level, and the Living by Chemistry curriculum19 for high

### BIG IDEAS

In curriculum design, the term “big idea” traditionally refers to a statement that summarizes core knowledge in a discipline that we would like students to understand. For example, the statement “all matter is particulate in nature” may be considered a big idea in chemistry. Although the notion of organizing science curricula around big ideas has been around for over 20 years, many prospective and novice teachers have serious difficulties identifying big ideas in their area of interest. When asked to state a big idea in chemistry that their students should understand, many of my prospective chemistry teachers say things like “they need to know about bonds”, or “they need to understand chemical reactions”, instead of clearly expressing the specific enduring understandings that they want students to develop.

Coming up with big ideas in chemistry, or even a subfield of our discipline, is not an easy task, particularly when one has never been exposed to or asked to think about them. However, there are insightful works that can be used to initiate discussions and reflections about chemistry content from a “big ideas” perspective. For example, Ronald Gillespie11 and Peter Atkins,12 two well-known and respected chemistry educators, have independently identified and discussed what they consider big ideas in the discipline (see Table 2). More recently, the College Board has published a set of standards for college success that includes a collection of enduring understandings that nicely summarize big ideas for introductory chemistry courses at the secondary school and college levels.13 Similar ideas can be found in the recent National Research Council (NRC) Framework for K–12 Science Education14 and the anchoring concepts content maps developed by the ACS Examinations Institute.15,16

Asking teachers to critically analyze these types of documents could shift their attention from the topics to be covered in a chemistry course to the big ideas students should develop. It could also help chemistry teachers build more meaningful connections between different concepts in the chemistry curriculum. Teachers and instructors could also benefit from reviewing examples of curriculum projects for introductory chemistry that have explicitly used big ideas as organizing principles. That is the case of the Chemistry X11 curriculum15 and the Chemistry, Life, the Universe and Everything (CLUE) project18 at the college level, and the Living by Chemistry curriculum19 for high

### Table 1. Typical Major Categories and Subcategories of Chemistry Knowledge Identified by Introductory Chemistry Teachers

<table>
<thead>
<tr>
<th>Chemical Structure</th>
<th>Chemical Reactivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical language (formulas, nomenclature)</td>
<td>Chemical reactions (reaction types, stoichiometry)</td>
</tr>
<tr>
<td>Atomic structure</td>
<td>Chemical kinetics</td>
</tr>
<tr>
<td>Molecular structure</td>
<td>Chemical thermodynamics</td>
</tr>
<tr>
<td>Properties of matter</td>
<td>Chemical equilibrium</td>
</tr>
</tbody>
</table>

the areas of chemical education research and practice, history and philosophy of chemistry, as well as in the development of chemistry education standards, provides the basis from which this type of pedagogical content knowledge may be developed. Borrowing from ideas and results from a variety of studies in those fields, in the following sections I describe 10 different perspectives or “facets” from which one may approach thinking and reflecting about chemistry subject matter (Box 1). I see these facets as complementary rather than competitive perspectives on how to conceptualize the content of introductory chemistry courses at the high school and college levels. My goal is not to present an exhaustive exploration of different levels of analysis of our chemistry knowledge, but rather to make explicit our discipline, is not an easy task, particularly when one has never been exposed to or asked to think about them. However, there are insightful works that can be used to initiate discussions and reflections about chemistry content from a “big ideas” perspective. For example, Ronald Gillespie11 and Peter Atkins,12 two well-known and respected chemistry educators, have independently identified and discussed what they consider big ideas in the discipline (see Table 2). More recently, the College Board has published a set of standards for college success that includes a collection of enduring understandings that nicely summarize big ideas for introductory chemistry courses at the secondary school and college levels.13 Similar ideas can be found in the recent National Research Council (NRC) Framework for K–12 Science Education14 and the anchoring concepts content maps developed by the ACS Examinations Institute.15,16

Asking teachers to critically analyze these types of documents could shift their attention from the topics to be covered in a chemistry course to the big ideas students should develop. It could also help chemistry teachers build more meaningful connections between different concepts in the chemistry curriculum. Teachers and instructors could also benefit from reviewing examples of curriculum projects for introductory chemistry that have explicitly used big ideas as organizing principles. That is the case of the Chemistry X11 curriculum15 and the Chemistry, Life, the Universe and Everything (CLUE) project18 at the college level, and the Living by Chemistry curriculum19 for high

### Box 1. Ten Facets on Chemistry Knowledge for Teaching

1. Big Ideas
2. Essential Questions
3. Cross-Cutting Concepts
4. Conceptual Dimensions
5. Knowledge Types
6. Dimensional Scales
7. Modes of Reasoning
8. Contextual Issues
9. Philosophical Considerations
10. Historical Views

### Table 2. Big Ideas in Chemistry Identified by Different Authors

<table>
<thead>
<tr>
<th>Ronald Gillespie11</th>
<th>Peter Atkins12</th>
<th>College Board Standards13 (Examples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Atoms, molecules, and ions are the basic components of matter.</td>
<td>1. Matter consists of about 100 elements.</td>
<td>1. All matter is made of atoms.</td>
</tr>
<tr>
<td>2. Chemical bonds are formed by electrostatic attractions between positively charged cores and negatively charged valence electrons.</td>
<td>2. Elements are composed of atoms.</td>
<td>2. The atoms of each element have unique structures arising from interactions between electrons and nuclei.</td>
</tr>
<tr>
<td>3. Atoms in molecules and crystals arrange in particular geometries.</td>
<td>3. The orbital structure of atoms accounts for their periodicity.</td>
<td>3. Elements display periodicity when organized according to increasing atomic number.</td>
</tr>
<tr>
<td>4. Atoms and molecules are in constant motion.</td>
<td>4. Chemical bonds form when electrons pair.</td>
<td>4. Atoms are conserved in physical and chemical processes.</td>
</tr>
<tr>
<td>5. Atoms in molecules and crystals can reorganize to form new molecules and crystals.</td>
<td>5. Shape is central to function.</td>
<td>5. The strong electrostatic forces of attraction holding atoms together in a unit are called chemical bonds.</td>
</tr>
<tr>
<td>6. Reactions occur when the disorder of the universe is increased.</td>
<td>6. Molecules attract and repel each other.</td>
<td>6. Chemical and physical transformations typically involve a change in energy.</td>
</tr>
<tr>
<td></td>
<td>7. Energy is blind to its mode of storage.</td>
<td>7. Breaking bonds requires energy, and making bonds releases energy.</td>
</tr>
<tr>
<td></td>
<td>8. Reactions fall into a small number of types.</td>
<td>8. Chemical equilibrium is a dynamic, reversible state in which rates of opposing processes are equal.</td>
</tr>
<tr>
<td></td>
<td>9. Reaction rates are summarized by rate laws.</td>
<td></td>
</tr>
</tbody>
</table>
school chemistry. The advantage of these approaches is that they facilitate the development of core concepts using coherent sets of learning progressions interwoven throughout the curricula.

**ESSENTIAL QUESTIONS**

In traditional approaches to school chemistry, students are introduced to a variety of concepts, ideas, and experimental methodologies without much discussion of their power as theoretical and practical tools in answering relevant questions about the world. From this perspective, chemistry teaching may benefit from the careful analysis of the intellectual purposes of the discipline and the essential questions that chemistry knowledge helps us answer. In the NRC report *Beyond the Molecular Frontier,* a committee of prominent chemical scientists and engineers nicely summarized the central goals and challenges of modern chemistry. Without any reference to specific topics or standard academic subdivisions (e.g., analytical, organic, or physical chemistry), this document identifies four main activities, and associated essential questions, that seem to characterize chemistry as a discipline:

1. Analysis (What is it?)
2. Synthesis (How do I make it?)
3. Transformation (How do I change it?)
4. Modeling (How do I explain it?)

The recognition of the essential questions that chemical knowledge allows us to answer can help teachers reconceptualize the ways in which concepts and ideas are introduced and discussed in the chemistry classroom. It can help reshape chemistry content in ways that are more motivating, meaningful, and useful for the students we serve. For example, in the Chemistry XXI project for college general chemistry, units of study are guided by questions that reflect central quests in our discipline, such as: How do we differentiate substances? How do we predict their properties? How do we control chemical reactions? How do we synthesize chemical substances? How do we harness chemical energy? This curriculum engages students in seeking and exploring the answer to such questions in the context of analyzing relevant problems for modern society (e.g., health, environment, food, energy issues). One of the benefits of this approach is that it allows students to recognize the power of chemical concepts, ideas, and ways of thinking in answering critical questions in diverse contexts.

**CROSS-CUTTING CONCEPTS**

The traditional approach to the presentation of chemistry content in introductory courses can easily conceal underlying conceptual threads or common ways of thinking across the curriculum. Approaching the analysis of course content looking to identify cross-cutting concepts or unifying themes may help teachers make those connections more explicit. Documents such as the *Benchmarks for Science Literacy,* the *National Science Education Standards,* and the new *Framework for K–12 Science Education* have already highlighted major overarching concepts across diverse scientific disciplines. Some of these concepts (e.g., structure and function, patterns, cause and effect) are central to chemistry at all educational levels, although instructors need to identify, analyze, and reflect about how those cross-cutting concepts are embedded in the chemical models and explanations typically discussed in different chemistry classrooms.

Thinking about cross-cutting concepts could lead us to reshape the chemistry curriculum to emphasize major themes instead of isolated topics. For example, we could focus our educational efforts on helping students understand, explain, and predict structure–property relationships across different types of substances. We could organize the presentation of content looking to explore how the analysis of patterns in physical and chemical properties can be used to build models to explain and predict the behavior of different types of substances. We could highlight the different models of causality typically used to explain different types of physical and chemical phenomena (e.g., direct causality versus emergent causality), as well as the different mechanisms associated with each of them.

Emphasis on these cross-cutting concepts may facilitate focusing students’ attention on the fundamental elements of the chemical models used to understand and transform matter rather than on the superficial features. This emphasis may also help build more authentic connections with real-life contexts, as illustrated by the chemistry units developed by Meijer and collaborators centered on the use of structure–property relationships as arguments in the solution of relevant problems, such as the design of a flexible bullet-proof vest, or the development of gluten-free bread. Focusing on unifying concepts may also result in more meaningful learning, as revealed by recent educational research involving college students enrolled in general chemistry courses using the CLUE curriculum. This curricular approach follows a carefully crafted learning progression around the cross-cutting theme of structure and function. Research findings indicate that students in the CLUE classes attain higher levels of representational competence than their peers enrolled in conventional general chemistry classes.

In particular, CLUE students were better at drawing Lewis structures of simple and complex molecules, as well as understanding the chemical information implicitly encoded within such structures.

**CONCEPTUAL DIMENSIONS**

Chemistry content can also be analyzed in terms of the main physical properties around which chemical models and explanations are built. These physical properties define conceptual dimensions commonly used in chemistry to analyze and describe the behavior of chemical systems. For example, William Jensen has suggested that the concepts and models of chemistry can be divided into three main dimensions: Composition and Structure, Energy, and Time. These conceptual dimensions are similar to those identified as major progress variables in the Perspective of Chemists framework designed by Claesgens et al. to describe and assess the development of student conceptual understanding in chemistry. In this assessment framework, big ideas and essential questions in chemistry are organized along the conceptual dimensions of Matter, Energy, and Change. The use of these dimensions in the organization of high school chemistry curricula has been put to practice in the development of content and educational activities for the project Living by Chemistry.

Thinking about chemistry content in terms of conceptual dimensions could allow teachers to better identify, highlight, and contrast the scope and limitations of the chemical models and explanations discussed in the classroom. For example, students could be asked to discuss the strengths and weaknesses of thermodynamic models of matter, mostly based on the energy dimension, versus kinetic–molecular models of equivalent systems that incorporate the structure and time dimensions. Analysis of the subject matter based on conceptual dimensions could also help teachers recognize areas in the curriculum that need more attention. For example, current...
introductory chemistry courses at the secondary school level tend to emphasize the discussion of chemical models focused on the composition—structure and energy dimensions over those that consider the time dimension. This unbalanced approach may be in part responsible for the difficulties that students face in building explanations for phenomena that demand the analysis of competing simultaneous processes (e.g., chemical equilibrium).27

■ KNOWLEDGE TYPES

School chemistry content can also be analyzed from the perspective of the different types of disciplinary knowledge that we want students to develop. In particular, chemical educators often distinguish three relevant knowledge types:28–30

1. Experiences—Refers to the empirical knowledge that we have or gather, through the senses or using instrumentation, about chemical substances and processes: for example, iron rusts in the presence of air.

2. Models—Encompasses the theoretical models that chemists have developed to make sense of the experienced world: for example, rusting is a chemical process in which elemental iron reacts with elemental oxygen to produce iron oxide, a chemical compound.

3. Visualizations—Includes the different visual signs (from symbols to icons, from static diagrams to dynamic animations) used to facilitate reasoning and communication about both experiences and models in chemistry: for example, \(4\text{Fe}(s) + 3\text{O}_2(g) \rightarrow 2\text{Fe}_2\text{O}_3(s)\).

A considerable amount of research in chemical education indicates that students struggle to differentiate between these three types of knowledge, and that many chemistry teachers and instructors often fail to make a clear distinction between experiences, models, and visualizations discussed in the classroom.29 Research also suggests that many students are unable to build meaningful connections or translate information between these three types of knowledge for a given chemical system. These results highlight the importance of analyzing chemistry content from this perspective when planning classes. Teachers need to purposely engage students in exploring relevant chemical systems, building clear links between the three knowledge types. Failure to do so may perpetuate the naïve belief that understanding chemistry is about learning to skillfully manipulate its visual symbols rather than to meaningfully apply models to make sense of and control real experiences in our world using visualizations as tools for thinking.

The innovative curriculum Connected Chemistry (CC)31,32 for high school chemistry is an excellent example of an educational project focused on helping students build an integrated view of chemical systems applying and connecting different knowledge types. A critical component of this curriculum is an interactive computer-based learning environment that structures and records students’ activities. Students working with the CC curriculum exhibit significant gains in the understanding of submicroscopic models of matter and of how such models can be used to describe, explain, and predict macroscopic experiences.33

■ DIMENSIONAL SCALES

Chemists explore, model, and build visualizations of the properties of matter at different length, time, and energy scales. Thus, chemistry content can also be analyzed by considering the different scales at which descriptions, explanations, or predictions are built in the classroom. In general, it is common for chemical educators to refer to the macroscopic and particulate levels of analysis in chemistry.28,29 However, this dichotomic view may conceal the existence of other relevant scales in the analysis of chemical systems or may lead teachers and instructors to overemphasize descriptions at some scales over others. In terms of length scales, for example, chemical models and explanations may be developed at various levels: macroscopic, multiparticle, mesoscopic, supramolecular, molecular, and subatomic.30 Recognizing these different levels of description is important for teachers because one can expect students to have problems connecting or translating concepts and ideas defined at each of these different length scales.

Current chemistry curricula and teaching practices tend to focus on descriptions at the molecular (single particle) and subatomic levels, regardless of the nature of the system. Rarely are students asked to explore, for example, mesoscopic models of matter that are critical in the analysis of important materials such as polymers and ceramics,33 or to analyze supramolecular systems despite their relevance in understanding living organisms. It is also uncommon for chemistry teachers to engage students in the exploration and reflection of chemical properties and processes that manifest or occur in different energy and time scales. One could thus envision an innovative chemistry curriculum in which the focus was to engage students in exploring, building, and connecting models of chemical substances and processes built at different length, time, and energy scales, as well as in comparing, contrasting, and evaluating the explanatory and predictive powers of such models. Deeper analysis and reflection about the various dimensional scales in which chemical knowledge resides could help students understand how to apply chemical models and ideas to explore systems as diverse as a cell, a piece of plastic, or a star.

Along these lines, the CLUE curriculum18 for introductory college chemistry is a good example of how dimensional scales can be thoughtfully used to organize chemistry content. In this case, concepts and ideas are presented along the composition—structure dimension, analyzing chemical systems with increasing levels of complexity, from atoms to molecules to macromolecules to cellular environments. The educational units developed by Meijer and collaborators23 illustrate how to use dimensional scales as guides in the development of authentic tasks that focus students’ attention on macro to micro connections in relevant contexts.

■ MODES OF REASONING

Chemistry is commonly depicted as a prototypical science focused on describing, explaining, and predicting the properties and behavior of chemical substances and processes. To accomplish this task, chemical scientists construct, evaluate, and revise models about the systems of interest. Model-based reasoning involves using or constructing models consistent with existing prior knowledge and evidence, comparing and evaluating the ability of different models to explain observed properties and predict new phenomena, and revising models to increase their explanatory and predictive power. Analyzing chemistry content from a “modeling” perspective is thus critical in identifying opportunities for students to get involved in this type of reasoning.

Interestingly, chemistry has also been characterized as a “technoscience” that mixes scientific pursuits with technological goals.34 Chemical scientists are not only interested in explaining and predicting the properties of chemical substances; they also want to transform them and create new chemical entities with potential applications. From this perspective, both modeling...
and design should be seen as central practices in the discipline. Thus, school chemistry should also involve students in design practices such as identifying design criteria, specifying constraints, and relying on known cases and empirical rules to identify best solutions.\textsuperscript{35} This suggests that content analysis in chemistry would benefit from carefully analyzing opportunities for learners to engage in three major types of reasoning: model-based, case-based, and rule-based reasoning. Besides chemical models, a significant portion of chemistry knowledge is organized in sets of interconnected classification systems in which known types of chemical substances and reactions serve as paradigmatic cases that help chemists make effective decisions about potential synthetic routes or methods of analysis.\textsuperscript{36} As is common in the technological world, chemists also rely on the thoughtful application of a variety of empirical generalizations used as heuristics or rules-of-thumb to make quick decisions. Research has shown that chemistry students need support in better identifying when and how to apply model-based, case-based, or rule-based reasoning, depending on the nature of the tasks that they confront.\textsuperscript{37,38}

To my knowledge, there are no curricular initiatives that have tackled the task of creating learning environments that support the three types of reasoning analyzed in this facet. However, there are innovative projects, such as Connected Chemistry,\textsuperscript{31–33} that structure students’ learning experiences through the exploration of models. There are also excellent, freely available online learning environments, such as the Molecular Workbench,\textsuperscript{39,40} that can be used to actively engage students in using and constructing models of diverse physical and chemical systems. Engaging learners in modeling activities has been shown to help them build subject matter knowledge, as well as develop a better understanding of how chemical knowledge is generated.\textsuperscript{41}

\section*{CONTEXTUAL ISSUES}

Chemistry teachers recognize the importance of chemistry and its products for modern societies. However, we often fail to take advantage of the centrality of chemistry in the modern world to help students learn in more meaningful ways. This failure likely stems from limited analysis of and reflection on how the chemistry content that we teach is relevant in different contexts, as well as how to use such contexts to engage students in knowledge construction.\textsuperscript{42} Educational research suggests that relevant contexts provide productive settings for learning when students participate in communities of practice engaged in addressing well-defined problems that require meaningful use of chemistry concepts and ideas.\textsuperscript{43} The identification of productive learning tasks demands the critical analysis of the chemistry content to be taught in relation to its areas of application. Such analysis could help teachers identify learning opportunities for students to apply chemical knowledge and ways of thinking in at least three main ways:

1. \textit{Explanatory-Predictive:} Students generate models of entities and processes that can explain and predict relevant phenomena, such as the effect of greenhouse gases in the atmosphere. Contextual issues are used to involve learners in analyzing data, building models and explanations, generating and defending arguments based on evidence, as well as reaching consensus on ways of representing and communicating their ideas.

2. \textit{Transformative:} Students design substances or processes to address relevant problems, such as purifying sewer water in their community. Contextual issues are used to involve learners in defining specifications, identifying constraints, as well as designing, testing, and revising prototypes based on their knowledge and experiences.\textsuperscript{73}

3. \textit{Socio-Chemical:} Students analyze, synthesize, and evaluate the social, economical, and environmental costs and benefits of chemical activities or the use of chemical products, such as consuming plastic packaging. Contextual issues are used to involve learners in making decisions that demand the consideration of moral and ethical issues, together with a sound understanding of core chemistry concepts, ideas, and practices.\textsuperscript{44}

Of all of the different facets of chemical knowledge described in this contribution, the contextual perspective may be the one that has led to the larger number of innovative curricular projects in our discipline. In the United States, initiatives such as Chemistry in the Community\textsuperscript{45} for high school chemistry, Chemistry in Context\textsuperscript{46} for nonscience college majors, and the ChemConnections\textsuperscript{47} modular approach for college general chemistry are excellent models of reform shaped by the context facet. Similarly, Salters Chemistry\textsuperscript{48} in the United Kingdom, Chemie im Kontext\textsuperscript{49} in Germany, and Chemistry in Practice\textsuperscript{50} in The Netherlands are exemplary instances that illustrate what can be achieved when relevance is at the center of the chemistry curriculum.

Educational research linked to these different programs suggests that students’ interest, attitudes, and motivation for learning chemistry are heightened by context-based approaches, and that their conceptual understanding may also benefit when such approaches are properly implemented.\textsuperscript{51}

\section*{PHILOSOPHICAL CONSIDERATIONS}

Publications on the philosophy of chemistry have increased considerably in the past 20 years.\textsuperscript{52–55} Work in this area has revealed critical features of the chemical enterprise, as well as of the knowledge that it generates, that make it distinct from other scientific disciplines. Analyzing and reflecting on these unique features can help teachers and instructors challenge and enrich their understanding of chemistry, both as a practice and as a body of knowledge. Although the implications of existing philosophical studies for the teaching and learning of chemistry have just begun to be elaborated,\textsuperscript{56} important areas for content analysis and reflection include these:

\textit{Chemical Concepts:} Chemistry is categorized as a physical science and people often assume that chemical concepts may always be reduced or explained in terms of fundamental principles of physics. However, there is considerable debate about the reducibility of many core chemical concepts such as composition, structure, chemical bonding, or aromaticity.\textsuperscript{53,54} Understanding the nature of this debate may help chemical educators better recognize the power, scope, and limitations of the concepts we teach and the explanations we build.

\textit{Chemical Laws:} While the major laws of physics, such as the laws of conservation of energy, are considered exact as they are expected to always be valid given proper constraints, philosophers of chemistry point out that many of the laws of chemistry are approximate, exceptioned, or imprecise.\textsuperscript{52} A more careful analysis of the nature of the laws, principles, and rules-of-thumb that guide chemical thinking is required if we want students to better judge and use their explanatory and predictive powers.

\textit{Chemical Models:} Chemical scientists build and make use of models in ways that are distinct from other scientific disciplines. For example, they may describe the same phenomenon using different (e.g., Arrhenius, Bronsted–Lowry, and Lewis models...
of acidity) or competing (e.g., valence bond or molecular orbital models of chemical bonding) models, adopting whichever one seems best adapted for their purposes. This "multiplicity" in modeling can be quite confusing for students and thus should be recognized and reflected upon by teachers.

Chemical Language: Chemical thinking largely relies on a rather complex system of symbols and icons that are not only used to communicate information, but are critical in the construction of explanations and in the design of new products. How chemists use this symbolic language to bridge the world of laboratory experiences and the world of molecular models is the subject of much philosophical analysis. Engaging in such discussions may give teachers ideas about how to best support the development of chemical fluency.

Specific ideas of how to incorporate philosophical perspectives in chemical education can be found in an issue of the journal Science & Education dedicated to this particular topic.

■ HISTORICAL VIEWS

Chemistry is presented in most modern textbooks from a rather ahistorical perspective. Although references to major figures in the history of the discipline are often made, little discussion and analysis is offered of the central questions, dilemmas, and concerns that have driven the development of chemical ideas and practices. There is also no clear depiction of how the roles and perceptions of chemistry as a human endeavor have evolved over time. Looking at chemistry from a historical perspective is beneficial to chemical educators because it helps us recognize struggles in the understanding of central concepts and big ideas in the discipline, many of them similar to the challenges that students face in our classrooms. It also opens our eyes to the underlying themes, essential questions, scales of analysis, conceptual dimensions, contextual issues, and philosophical considerations that have emerged from the work of chemists throughout the ages.

Consider, for example, the historical analysis of Jensen on the major "revolutions" in the history of the discipline. In this work, Jensen builds a connection between critical historical stages in the development of chemistry as a scientific discipline and changes in the scale of analysis of chemical systems within the composition—structure conceptual dimension, from the molar (macroscopic), to the molecular, to the electrical (subatomic) levels. From a different perspective, Knight’s work follows the evolution of ideas in chemistry to reveal the different roles the discipline has played over time, from an occult to a mechanical science, from an inductive to a deductive science, from a descriptive to a reduced science, from a useful to a service science. As a final example, the writings of Bensaude-Vincent and Simon, at the boundary between history and philosophy, make us reflect on the ethical dimensions of chemistry. Suggestions about how to use historical and philosophical perspectives in the teaching of general chemistry have been made by several authors.

■ FINAL COMMENTS

One may consider that paying attention to all of the different facets of the chemistry knowledge discussed in this contribution would be impossible when planning a chemistry class. It would certainly be a Herculean task. Instead, I suggest that teachers and instructors engaged in teaching introductory chemistry courses at the secondary or college levels consider these preliminary actions:

Acknowledge the existence of these facets
Open space in busy schedules to explore, analyze, and reflect on at least one of the facets
Dare to make some changes in teaching that reflect a more multifaceted understanding of the chemistry content

From my perspective, the 10 facets reveal the multidimensional nature of chemistry as a teaching subject. They elicit its complexity, yet also its richness and beauty. They also make explicit many reasons to question monolithic approaches to the chemistry curriculum that predominate in many schools and colleges across the world. Moreover, these 10 facets illustrate how intellectually demanding yet profoundly stimulating it can be to look more deeply at the content we teach.

■ AUTHOR INFORMATION

Corresponding Author
E-mail: vicente@u.arizona.edu

Notes
The authors declare no competing financial interest.

■ REFERENCES


