Let's teach how we think instead of what we know

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Despite multiple calls for reform, the curriculum for first-year college chemistry at many universities across the world is still mostly fact-based and encyclopedic, built upon a collection of isolated topics, oriented too much towards the perceived needs of chemistry majors, focused too much on abstract concepts and algorithmic problem solving, and detached from the practices, ways of thinking, and applications of both chemistry research and chemistry education research in the 21st century. This paper describes an alternative way of conceptualizing the introductory chemistry curriculum for science and engineering majors by shifting the focus from learning chemistry as a body of knowledge to understanding *chemistry as a way of thinking*. Starting in 2007, we have worked on the development and implementation of a new curriculum intended to: promote deeper conceptual understanding of a minimum core of fundamental ideas instead of superficial coverage of multiple topics; connect core ideas between the course units by following well-defined learning progressions; introduce students to modern ways of thinking and problem-solving in chemistry; and involve students in realistic decision-making and problem-solving activities.

Keywords: first-year undergraduate chemistry; general chemistry curriculum; evidence-based curriculum; curriculum design; curricular innovations

Introduction

In the past fifteen years a considerable amount of time and resources have been invested in the development and dissemination of projects designed to change the teaching practices in the first-year undergraduate chemistry curriculum. In the US, these efforts have led to high quality resources and innovative pedagogical practices, such as those produced by the National Science Foundation's Systemic-Change Initiatives (Burke *et al*., 2002), as well as the Process Oriented Guided Inquiry Learning initiative (Moog and Spencer, 2008), and the Science Writing Heuristic project (Burke *et al*., 2006). However, the focus of most of these programs has been on the development of learner-centered ways of teaching introductory chemistry, with only a few of them (*e.g. ChemConnections*) offering a truly alternative approach to the structure of the curriculum for science and engineering majors.

Although these initiatives have had a positive impact on the teaching practices of a significant number of instructors around the US, their effects have been more noticeable in liberal arts colleges and in a handful of research-extensive universities with strong science education traditions (Ege *et al*., 1997; Landis *et al.*, 1998; Burke *et al*., 2004). Institutional constraints and personal resistance to change have been more difficult to overcome in community colleges and large universities where general chemistry classes involve hundreds of ethnically and academically diverse students. In most of these types of institutions, the curriculum of introductory chemistry courses has remained practically unchanged for the past fifty years (Lloyd, 1992a, 1992b). Despite multiple calls for reform from chemical educators and professional associations (Gillespie, 1991, 1997; Bodner, 1992; Spencer, 1992; Lloyd and Spencer, 1994; Hawkes, 2005), the first-year chemistry curriculum at most universities is still mostly fact-based and encyclopedic, built upon a collection of isolated topics, oriented too much towards the perceived needs of chemistry majors, focused too much on abstract concepts and algorithmic problem solving, and detached from the practices, ways of thinking, and applications of both chemistry research and chemistry education research in the 21st century.

The strong resistance to curriculum and instructional reform in first-year college chemistry will be difficult to overcome without the development of viable and coherent educational models that can be adopted with relative ease and at a low cost for most institutions of higher education. These models must represent authentic alternatives to the traditional curriculum, but must not be conceived as less 'rigorous' by the chemistry faculty. The models should foster meaningful learning of a minimum core of central ideas in the discipline, address issues of relevance for diverse students, and incorporate contemporary ways of thinking, modeling, and problem-solving in chemistry (Mbajiorgu and Reid, 2006). The nature of these educational models may be varied, but there is an urgency to develop high-quality and refreshing curricular approaches to the teaching of introductory chemistry courses at the college level. We need more creative and meaningful curricular options; we need more discussions that can help us reconceive the general chemistry curriculum. The present work seeks to contribute to the much needed debate in this area by describing an innovative curriculum project at our institution, a public research-extensive university in the south-western United States with a diverse

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student population (53% female, 47% male; 32% from minority groups, mostly Hispanic).

Current approaches

Although the content of the first-year chemistry courses over the past 100 years has switched from having a strong emphasis on descriptive inorganic chemistry during the first half of the twentieth century to fundamental physical chemistry in the last fifty years, the main goal of these introductory courses has changed very little: to introduce students to the most important knowledge, fundamental laws, principles, theories, and applications of chemistry (Lloyd, 1992a, 1992b). The history of general chemistry is clearly imprinted on the popular textbooks that have been used throughout this period. What began as a compendium of facts about chemical elements and their reactions has become an encyclopedia of theoretical principles and their applications. From the emphasis on the description of innumerable properties, preparation methods, and industrial applications, we have moved to the description of multiple laws and principles and the rote application of mathematical algorithms to solve word problems.

The current first-year chemistry curriculum, as outlined in most chemistry textbooks, follows what has been called a 'topical ladder approach' (Schwartz, 2006). The content is introduced as a linear progression of concepts that tend to build on each other in a cumulative fashion (***e.g.*** Step 1. Matter and Measurement; Step 2. Atoms and Molecules; Step 3. Formulas and Equations; Step 4. Atomic Structure). Unfortunately, many students do not see the connections between the successive steps, much less among the different rungs of the ladder. Several research studies have shown that many students enrolled in general chemistry courses that follow the 'topical ladder approach' do not develop adequate conceptual understanding of the central concepts in the discipline, and are unable to transfer their knowledge to solve problems in different situations (Nurrenbern and Pickering, 1987; Gabel and Bunce, 1994).

A variety of authors have discussed the many limitations of the traditional first-year chemistry curriculum (Gillespie, 1991, 1997; Bodner, 1992; Spencer, 1992 Lloyd and Spencer, 1994;; Hawkes, 2005). It is too broad, too disconnected, too abstract, too irrelevant, too algorithmic-problem-solving oriented. A recent analysis of traditional high-school chemistry textbooks (Evans *et al*., 2006), which in many ways mirror those used at the college level, shows that almost half of the textbooks' content is dedicated to describing and explaining a large collection of facts and principles, while the other half is devoted to building a mastery of a collection of isolated skills and procedures: how to balance chemical equations, how to assign chemical names, how to build electron configurations or Lewis structures, etcetera. In this sense, the general chemistry curriculum is like a giant toolbox full of tools that students must learn how to use without context or a meaningful purpose. This curriculum fails to offer opportunities for most students to learn how to approach realistic problems from a chemical perspective, using the powerful and productive models, techniques, and ways of thinking developed in the field.

The existing alternative to this curricular model for the first year of college chemistry for science and engineering majors is best captured by the *ChemConnections* modular approach (Anthony *et al*., 1998). This curriculum is highly influenced by the *ChemCom* (ACS, 2001) and *Salter's Chemistry* (Bennett and Lubben, 2006) models for high-school chemistry, and the *Chemistry in Context* approach for students who are not specializing in science (ACS, 2000; Schwartz *et al.,* 1994). In all these cases, the curriculum is mostly centered on real-world problems and issues with significant chemical content. In contrast with the vertical nature of the traditional curriculum, these types of context-based curricula have a more horizontal structure that can be thought of as a 'topical spider web' (Schwartz *et al*., 1994) in which chemical phenomena, facts, and principles are introduced on a need-to-know basis, making a strong emphasis on interdisciplinary connections. The few research studies designed to investigate the efficacy of these types of approaches have shown that students enrolled in these courses perform at the same level or better than those in traditional sections, and that, in general, they end up having better attitudes towards chemistry (Gutwill-Wise, 2001).

Despite its innovative and education research-based approach, the context-based curricular models for chemistry teaching have various limitations. For example, connections between concepts and ideas presented when discussing central course topics (*e.g*. ozone depletion, energy sources, global warming) may not be apparent to the students and the courses may become highly fragmented. Context-based approaches focus on the application of specific chemical ideas to understand an issue, and they do not necessarily connect ideas from one topic to another or emphasize patterns of reasoning that can be applied to different situations (Reid, 2000). These types of curricular models are also frequently perceived as 'chemistry lite', excessively descriptive, or difficult to implement by many faculty. Understanding complex environmental or societal issues requires the introduction of considerable amounts of descriptive information that instructors may consider non-essential in a chemistry course.

The 'topical ladder' and 'spider web' approaches define the two ends of the narrow spectrum of curricular models available for teaching first-year chemistry. In between these extremes we can find a few innovative projects tilted in either direction. For example, the recent text *Chemistry* (ACS, 2005), sponsored by the American Chemical Society, represents a commendable effort to reduce the breadth and increase the depth of a ladder-type curriculum, while simultaneously introducing applications of chemical ideas to biological systems. Without any demerit to the value of these innovative approaches, one can argue that all of them think of the chemistry curriculum as an avenue to communicate what chemists 'know' and can explain with that knowledge. Their focus is mainly on the content and its applications. We would like to contend that an alternative way to visualize the curriculum is to focus on *how chemists 'think'* and how *chemical ways of reasoning* can be used to solve significant and realistic problems in many areas. This is the philosophy that guides the curriculum proposal described in the next section.

A new model

In the recent US National Research Council (NRC) report *Beyond the Molecular Frontier* (2003) a committee of expert chemists and chemical engineers nicely summarized the goals and the challenges for the chemical sciences in the 21st century. The report describes how chemical thought and practices can help us address many of the critical issues that humans will face in the upcoming years. Beyond standard academic subdivisions such as analytical, biochemical, inorganic, physical, and theoretical chemistry, the document identifies four main activities, and essential questions, that characterize the work of modern chemical scientists: *analysis (what is it?)*, *synthesis (how do I make it?)*, *transformation (how do I change it?)*, and *modeling (how do I explain it)*. Additionally, the report describes the associated challenges in what are perceived as the most important application areas: *Energy sources*, *environmental issues*, *life and medicine*, and *materials by design*. From our perspective, the work of the NRC committee provides an excellent blueprint for what an authentic first-year chemistry curriculum ought to be: A curriculum that provides opportunities for science and engineering majors to

a) *recognize* the essential questions that our modern chemical knowledge and practices allow us to answer,

b) *explore* and understand the theoretical and practical tools that have been developed to find these answers, and

c) *apply* these ideas and techniques in the investigation of relevant problems.

With these overarching questions, themes, and goals in mind, since the spring of 2007 we have worked on the development and testing of a modern general chemistry curriculum that can better serve the educational needs of the scientists and engineers of the 21st century. Specifically, we have strived to create a curriculum approach that:

- shifts the attention from learning chemistry as a body of knowledge to focus on understanding chemistry as a way of thinking;
- promotes deeper conceptual understanding of a minimum core of fundamental ideas instead of superficial coverage of multiple topics;
- connects core ideas between the course units by following well defined learning progressions;
- takes into account the results from science and chemistry education research on how people learn in order to develop a sound curricular sequence and associated learning activities;
- introduces students to modern ways of thinking, modeling, decision-making, and problem-solving used in chemistry;
- involves students in realistic decision-making and problem-solving activities in areas of interest for the science and technology of the 21st century without losing intellectual rigor.

To develop *Chemistry XXI*, our proposed new curriculum, we used a backward design model (Wiggins and McTighe, 1998). Following this approach, the first step was to identify the desired results in terms of the *enduring understandings* we wanted general chemistry students to develop. Then, we defined the *assessment tools* that would allow us to evaluate progress towards the stated learning goals. Finally, we developed, adopted, or adapted the *learning experiences* that would help students achieve the desired goals. In the following subsections, we describe the core components of our proposed chemistry curriculum using these three basic design components as a guideline for the presentation.

1. Enduring understandings

The *Chemistry XXI* project was developed under the premise that it would be beneficial to shift the focus of the first-year chemistry curriculum from acquiring core chemical knowledge, to mastering core 'chemical ways of thinking'. It is important to point out that by *chemical ways of thinking* we are not referring to the general process, problem-solving, or critical thinking skills that have been identified as useful in learning sciences and other disciplines (*e.g.* observing, inferring, identifying and controlling variables, evaluating answers, monitoring decisions). Although we are convinced that the development of these domain-general reasoning skills should be fostered in the introductory chemistry classroom, our intent is to focus the attention on the domain-specific chemistry-based ways of thinking that have proven to be so powerful and successful in analyzing, modeling, and transforming our surrounding world. The central tenet of the new curriculum is that these chemical ways of thinking are the transferable skills that science and engineering majors will find useful in their futures studies, careers, and personal lives.

To clarify what we actually mean by 'chemical ways of thinking', let us consider a specific example. Chemists have developed a variety of models and techniques to detect, identify, separate, and quantify the amount of the different substances present in a system of interest, from the air that surrounds us to our inner body. The intellectual and practical tools of chemistry allow us to answer essential questions such as: What is this made of? Is this substance present? How do we isolate it? How much of it do we have? in a variety of crucial and relevant contexts for modern society, from analyzing pollutants in the environment to nutrients in our food, medicinal drugs in plants, or energetic resources inside our planet. Chemists have thus developed a very powerful and effective 'analytical way of thinking' based on fundamental assumptions such as:

- All chemical substances have at least one property that differentiates them from the others and defines their identity. Once a differentiating characteristic is identified for a given substance, we can use it to detect, separate, identify, and quantify this substance by selecting appropriate methods to probe for that property, measure the response to the probe, and interpret the measurement data to obtain the desired information.

We contend that recognizing, discussing, practicing, and reflecting on how to go about analyzing chemical substances in relevant contexts, particularly in the areas of *energy sources*, *environmental issues*, *life and medicine*, and *materials by design*, are some of the core skills that science

Table 1 Sequence of units and modules in the *Chemistry XXI* curriculum

Units	Modules*	Core chemistry concepts
Unit 1	M1. Searching for differences	Differentiating characteristic
	M2. Modeling matter	Phase transitions
How do we distinguish substances?	M3. Comparing masses	Particulate model of matter
	M4. Determining composition	Element/compound; atom/molecule
		Mole and molar mass
		Elemental composition
Unit 2	M1. Analyzing light-matter interactions	Light-matter interactions
	M2. Looking for patterns	Atomic structure
How do we determine structure?	M3. Predicting geometry	Covalent bonding
	M4. Inferring charge distribution	Molecular geometry
		Molecular polarity
Unit 3		Intermolecular forces
	M1. Analyzing molecular structure	Molecular compounds
How do we predict properties?	M2. Considering conformations	Macromolecular compounds
	M3. Characterizing ionic networks	Ionic compounds
	M4. Exploring electronic structure	Metallic systems
Unit 4		Chemical reaction
	M1. Understanding proportions	Conservation of matter and energy
How do we model chemical change?	M2. Tracking energy	Collision model
	M3. Analyzing rate and extent	Reaction rate and extent
		Chemical equilibrium
Unit 5	M1. Analyzing structure	Enthalpy and entropy of reaction
	M2. Comparing free energies	Free energy of reaction
How do we predict chemical change?	M3. Measuring rates	Rate law and reaction mechanism
	M4. Understanding mechanism	Thermodynamic/kinetic stability
Unit 6	M1. Characterizing interactions	Acids and bases
	M2. Changing the environment	Chemical equilibrium
How do we control chemical change?	M3. Analyzing the products	Charge stability
	M4. Selecting the reactants	Electronic/steric effects
		Thermodynamic/kinetic control
Unit 7		Basic chemical processes:
	M1. Tracking electron transfer	Electron transfer
How do we analyze chemical systems?	M2. Detecting electron sharing	Electron sharing
	M3. Analyzing coupled processes	Proton transfer
Unit 8	M1. Controlling electron transfer	Electrochemical processes
How do we harness chemical energy?	M2. Inducing electron transitions	Electronic processes

*Modules correspond to one to two weeks of course work in a two-semester sequence.

and engineering majors should have the opportunity to develop in the first-year chemistry classroom and laboratory. Thus, the first two units of our proposed curriculum (see Table 1) are focused on context-based discussions of how to go about analyzing chemical substances based on fundamental differentiating characteristics: phase behavior, molar mass, and chemical composition in Unit 1, and light absorption and emission, and atomic and molecular structure in Unit 2. These discussions occur in the context of analyzing important and interesting systems such as the main components of clean and polluted air (Unit 1), or the chemical composition of stars and greenhouse gases on our planet (Unit 2).

Given our focus on helping students develop fruitful ways of chemical thinking, one of the central tasks in our project was the identification of the central ideas that we believe guide chemical thought in the areas of *analysis*, *synthesis*, *transformation*, and *modeling* in chemistry. Together with the enduring understanding described in the previous paragraphs, the following core ideas define the six major thinking threads that cut across our new curriculum:

- The identity of a chemical substance is determined by its submicroscopic structure. The specific types, number, and arrangement of atoms or ions that comprise its molecules or the underlying ionic, metallic, or molecular network determine the physical and chemical properties of the substance.
- The submicroscopic *structure* of a chemical substance determines the nature of its *interactions*. Interactions between the submicroscopic components of different substances or with different forms of electromagnetic radiation may induce atomic or molecular rearrangements that change the properties of the substance or lead to the formation of new substances.
- Exploring and modeling how the properties of substances are related to the *structure, interactions, and dynamics* of their submicroscopic components helps design methods to separate, detect, identify, and quantify the substances, as well as procedures to synthesize or transform them.
- Exploring and modeling the effects of different types of *interactions* on the submicroscopic *structure* of substances, as well as the *mechanisms* through which structural changes may occur, help design methods to induce and control physical and chemical transformations.
- To synthesize or transform a chemical substance we should identify the intrinsic (structure) and extrinsic (environment) factors that may influence its thermodynamic and kinetic stability. The identification of characteristic atomic and electronic arrangements at the molecular level helps us

make predictions about chemical reactivity and likely reaction paths.

The six enduring understandings that undergird the *Chemistry XXI* curriculum encompass the major underlying assumptions that guide modern chemical thought as applied to the wide variety of systems in which it is relevant (NRC, 2003). This is not a list of ideas of what we know about the structure of matter or its transformations; nor is it a compendium of the fundamental chemical facts we have acquired about the surrounding world. This is rather a list of basic assumptions that guide chemical thinking as applied to the *analysis*, *synthesis*, *transformation*, and *modeling* of chemical systems, from the development of new materials or medicinal drugs, to the analysis of toxic materials or vital metabolites, to the search for alternative sources of energy or evidence of life on other planets. These are the types of ideas that reside at the heart of the discipline and that have enduring value beyond the chemistry classroom.

The development and selection of the core enduring understandings that are at the base of the new curriculum involved a cyclical process of analysis of the types of essential questions that chemists pose about the world, the underlying assumptions they make about its properties and behavior, and the intellectual and practical tools they use to generate answers. Some of these essential questions became the central inquiry that each of the units of the curriculum is designed to answer (see Table 1). Others served to define many of the exploratory activities that characterize the different course modules. Instead of using topics as the basic unit of design, we opted for using questions as drivers for the concepts and ideas to be discussed and analyzed along the curriculum (see Table 1 for a summary of core concepts addressed in every course unit). For example, the central query in chemical synthesis: *How do we make it?* opens opportunities for discussing the models, reasoning strategies, and techniques that have been developed to create new substances, from the analysis of the relationship between submicroscopic structure and chemical reactivity, to the discussion of thermodynamic and kinetic stability. The study and analysis of the chemical origin of biomolecules in our planet (Unit 5) and the design and production of pharmaceutical drugs (Unit 6) provide ideal contexts for the modules in which these ideas are explored and discussed.

In contrast with context-based approaches to the general chemistry curriculum, in which the central focus is on helping students understand a relevant phenomenon and the underlying chemistry, we focus instead on helping students recognize, develop, and apply the basic chemical models, ways of thinking, and practices that are fruitful in generating the answer to fundamental questions that modern scientists and engineers may pose (Reid, 2000). Differently from the ladder-approach to chemistry teaching, in which topics tend to be fully developed in single, encapsulated units (*e.g.* Atomic Structure, Thermodynamics, Kinetics), concepts and ideas in the *Chemistry XXI* curriculum are introduced as needed in order to answer the essential question of interest. To ensure curricular coherence and connectivity between concepts and ideas across course modules and units, we have paid close attention to the sequencing of the essential questions that drive the curriculum, looking to create appropriate learning progressions that take into account results from educational research in chemistry education. To illustrate these latter points, let us contrast how students are introduced to some of the submicroscopic models of matter used in chemistry in the traditional versus the *Chemistry XXI* curricula.

Research in science and chemical education has shown that, in general, students have serious difficulties understanding and applying the different assumptions of the atomic and molecular theories of matter (Nakhleh, 1992; Barker, 2000; Taber, 2002; Talanquer, 2006, 2009). Many authors have thus suggested grounding chemistry teaching in the analysis of the ‘macro’ world first, helping students develop particulate models of matter to explain their observations (Gilbert and Treagust, 2009). Unfortunately, many general chemistry textbook writers seem to disregard such evidence and suggestions, assuming that students are ready to delve into the subtleties of modern atomic theory from the moment they enter a college chemistry class. In fact, ‘innovative’ or ‘alternative’ general chemistry textbooks in the US are being marketed by promising a new ‘atoms-first approach’ in which the discussion of the electronic structure of matter has been moved earlier in the curriculum, to the beginning of the sequence of steps on the topical-ladder. The justification for this rearrangement is simple: to tell a more cohesive story about our chemistry knowledge starting from the fundamental blocks of matter and then moving to successively more complex structures. The proposed sequence is based on the logic of our disciplinary knowledge, but not necessarily on the evidence that we have about how to best facilitate student learning in chemistry.

Based on our analysis and interpretation of the education research literature on students’ ideas and learning of the submicroscopic models of matter, we considered it more appropriate to build a learning progression in which explorations and discussions about this topic follow what we call an ‘inquisitive spiral’, which begins and ends with the analysis of the macroscopic properties of relevant chemical substances and materials. Let us explain our approach in more detail. The sequence begins by having students recognize and explore those physical properties of substances that can be used to differentiate one from another (e.g. what physical properties can be used to separate the main components of our atmosphere?). This exploration creates and justifies the need to develop particulate models of matter that can be used to explain and predict those differences. To a first approximation, a multi-particle dynamic model in which substances are assumed to be composed of interacting particles in constant movement can be very useful. Thus, our discussions in the first unit of the *Chemistry XXI* curriculum move from the ‘macro’ level to the ‘multi-particle’ scale, emphasizing the dynamic nature of matter and the central role that interactions between particles play in determining their physical properties. Educational research tells us that even college students struggle to use this simple particulate model of matter to generate explanations and make predictions, and that these skills are crucial for understanding central concepts such as phase transition and chemical equilibrium (Nakhleh, 1992).

The discussions about the dynamic particulate model of matter naturally lead students to ponder why different particles exhibit different types of interactions. To answer this question, one must zoom into the molecular level and explore the internal structure of these particles (Unit 2). This task requires the discussion and application of basic techniques that can be used to explore particle composition and bonding patterns, such as elemental analysis, mass spectrometry, and infrared spectroscopy. Although we recognize the challenge of incorporating some of these topics as an integral part of the first-year chemistry curriculum, we are convinced that they can be meaningfully addressed at the appropriate level and that they are necessary to convey a realistic and engaging view of the nature and power of the modern chemical sciences. There are great examples in the chemical education literature that confirm the feasibility of introducing modern techniques in general chemistry courses (Spector, 1994; Nowak-Thompson, 2005).

The analysis of bonding patterns at the molecular level opens the door to discussions about the atomic models that can be used to explain them. This zooming into the atomic level can be done again by discussing the results of experimental techniques that allow us to explore matter at that scale (*e.g.*, emission and absorption spectroscopies, photoelectron spectroscopy). Current models of the atom are powerful tools in the explanation and prediction of the molecular structure of chemical compounds. Together with basic chemical models of bonding, they can be used to predict molecular geometry and polarity, as we zoom out to the molecular level with more powerful intellectual tools at hand. As we continue zooming out to the multi-particle level, we can now make predictions about different types of intermolecular forces among particles and analyze their effect on the physical properties of a variety of relevant chemical substances, from simple molecular compounds, to natural and synthetic macromolecular substances, to covalent, ionic, and metallic networks (Unit 3). Thus, in the first three units of the course, the *Chemistry XXI* curriculum takes students through a spiraled path (macro → multi-particle→ molecular → atomic → molecular → multi-particle → macro), helping them acquire intellectual and experimental tools that deepen their ability to describe, explain, and predict the physical properties of chemical substances using submicroscopic models of matter. A similar underlying approach is used in Units 4 through 6 to discuss and analyze chemical reactivity.

2. Assessment tools

The second stage in the backward design model of curriculum development focuses on the definition of clear learning outcomes and on the identification or construction of a sequence of assessment tools (diagnostic, formative, and summative) to collect the evidence that is needed to document and validate that the desired learning has been achieved. To design these assessment tools, we defined overarching learning goals for each course unit, together with central goals, ideas, and summative performance outcomes for each of the modules in a given unit. As an example, Table 2 presents these major design components for Module 4 of Unit 3: 'Exploring electronic structure' (Unit 3 in the course is largely focused on materials' analysis and design).

Table 2 Central learning goals, ideas, and objectives for Module 4 of Unit 3 of the *Chemistry XXI* curriculum

Unit 3

Overarching goal
To develop models and apply chemical ideas and techniques to explain and predict the physical properties of molecular and ionic compounds, as well as metallic and semi-metallic materials.

Module 4

Understanding goal:
To model, explain, and predict the physical properties of metallic and semi-metallic systems based on the crystalline arrangement and electron configurations of their atoms.

Central ideas:
- Most of the elements in our world are metallic. However, metals tend not to combine in definite proportions with other metals to form compounds. They mostly form mixtures.
- Atoms in crystalline metals are arranged in regular patterns. The crystalline structure of metals has an important effect on their physical properties such as ductility, brittleness, and density.
- Metal atoms tend to share their valence electrons with all the other atoms in the structure (metallic bonding). Valence electrons are delocalized, moving freely throughout the system (electron sea model). The existence of electrons that can freely move throughout a metallic system is responsible for their high electrical and thermal conductivities.
- Metals exhibit distinctive magnetic properties. In general, magnetism is a phenomenon associated with the presence of unpaired electrons in an atom. Thus, analyzing electron-configurations help us explain and predict magnetic properties.
- In solid metals the difference between energy levels that electrons occupy is negligible, and thus continuous 'energy bands' are formed. The relative energy of two of these bands, the valence band and the conduction band, determines whether the solid materials will be conductors, semiconductors, or insulators.

Performance objective:
Given information about the physical and electronic properties of different metals or semimetals, design a material, object, or device with specific characteristics.

Each module's central goals, ideas, and objectives were used to create diagnostic and formative assessment tools to gather evidence of student understanding across the module. These assessment tools were embedded in the daily class activities, which are described in more detail in the following subsection. However, to gather formative assessment data at the end of each module, we designed in-class performance tasks called 'Let's Apply' that are completed by students working in small groups. These activities require students to demonstrate and self-evaluate whether they have achieved the major performance outcome of the module. For example, for Module 4 of Unit 3 (see learning objective in Table 2), students are given information about physical and electronic properties of different metallic and semi-metallic materials (e.g. band gap energy, conductivity), and asked to design an LED (light emitting devices) capable of emitting red, green, or blue light. They are expected to justify all of their choices based on the central ideas discussed in the module. Other examples of 'Let's Apply' assessment activities in the *Chemistry XXI* curriculum include: Analysis of a star's temperature and chemical composition (Unit 2 Module 2); determination of the air/fuel ratio for a hydrogen-based car (Unit 4 Module 1); prediction of comparative acidities for commercial medicinal drugs (Unit 6 Module 3); estimation of the pH change of ocean water in the next 100 years (Unit 7 Module 3).

For summative assessment purposes, we considered it important to design instruments that would help us determine whether students could apply their knowledge and understandings to analyze realistic systems, or solve relevant multi-part problems, different from those discussed in class. In particular, we wanted to avoid the use of traditional exams in which students answer a set of disconnected questions designed to test isolated pieces of knowledge or specific skills. Given the size of general chemistry classes at our university (close to 300 students per section), we were limited in the type of summative assessment tasks we could satisfactorily evaluate. Thus, we opted for the design of what we called 'thematic tests' that require students to answer a set of interrelated short-answer questions about a relevant system or phenomenon. As an example, Table 3 shows one of the summative assessments we used for Unit 1 in which the overarching learning goal is for students *"to apply basic chemical ideas and techniques to distinguish the different substances in a system, describe and explain their physical properties using the particulate model of matter, and determine their molar mass and chemical composition."*

As shown in Table 3, our thematic tests begin with a short introduction designed to set the context for the system or problem of interest. This introduction frequently includes information in tabular or graphical form that may be useful to answer some of the assessment questions. This component of the task is provided to the students ahead of time, to give them the opportunity to carefully review, analyze, and reflect on the information. During the actual assessment, students work individually answering the test questions, which normally demand that they analyze and represent data in a variety of forms (*e.g.*, graphs, tables, diagrams, particulate drawings, chemical symbols). Different questions are used to help students build more knowledge about the system or problem under examination, putting special emphasis on those tasks that allow students to demonstrate meaningful understanding and integration of the central ideas of the module.

Based on contemporary views on education and assessment (Bransford *et al*., 2000; NRC,2001; Wilson and Scalise, 2006), learning in our new general chemistry curriculum is conceptualized not simply as a matter of acquiring more knowledge and skills, but as progress towards higher levels of competence in well defined areas. For this purpose, we have adapted or developed desirable learning progressions for core concepts and ideas in the curriculum (Claesgens *et al*., 2009; Wilson, 2009), looking to ensure that they are revisited at increasing levels of sophistication in the different course units. Consider, for example, the following learning progression associated with understanding the relationship between molecular interactions and physical properties of molecular compounds:

Level 1: Recognizes that differences in physical properties can be explained based on differences in the strength of attractive forces between submicroscopic particles (Unit 1).

Level 2: Relates the differences in the strength of intermolecular forces to differences in molecular structure and composition (Units 1 and 3).

Level 3: Explains differences in the strength of intermolecular

Table 3 Example of a thematic summative assessment for Unit 1

Context:

Titan or **Saturn VI** is the largest moon of Saturn, the only moon known to have a dense atmosphere, and the only object other than Earth for which clear evidence of stable bodies of surface liquid has been found. The *Cassini-Huygens* robotic spacecraft mission arrived in Saturn in 2004 and is currently studying the chemical composition of this planet and its moons, including Titan. The following table and graphs summarize important information about this moon:

(Supplied: Table including data about Titan's average surface temperature, pressure, air density, atmosphere and hydrosphere compositions; Graphs of atmospheric temperature and pressure profiles.)

Questions:

1. Figure 1 depicts the phase diagram of methane (CH_4), one of the main components of the atmosphere and hydrosphere in Titan. a) Identify the stable phase in each of the three major regions of the phase diagram; b) Identify the stable phase of CH_4 on the surface of Titan; justify your answer using the phase diagram; c) Can we expect to see CH_4 in gaseous form anywhere in this moon? If yes, at what altitudes? Use the available data to justify your answer.
2. Figure 2 depicts the vapor pressure graphs for methane (CH_4) and ethane (C_2H_6), the major components in Titan's hydrosphere. a) Estimate the temperatures at which each of these substances boils on the surface of Titan; b) Propose a strategy to separate these two components from a sample of Titan's hydrosphere; c) If you separated 10.0 g of a hydrosphere sample, what fraction of the particles in the sample would be ethane molecules? Use the available data to justify your answer.
3. Scientist have proposed that if the lakes of Titan were made of pure methane (CH_4) they would freeze when the wind blows and the lakes evaporate, even if the temperature of the atmosphere is slightly above the freezing point of CH_4. Use your knowledge about phase transitions and the particulate model of matter to evaluate whether this is a reasonable hypothesis.
4. A sample of the bottom of Titan's ocean (bottom of the hydrosphere) shows that one of the main components is a solid hydrocarbon. The analysis of this substance by mass spectrometry leads to the spectrum shown in Figure 4. Elemental analysis reveals the following compositions: 92.26% C and 7.74% H. Calculate the empirical and molecular formula of this chemical compound.
5. The same sample from the bottom of the ocean also contained solid water (H_2O). To analyze this substance, the ice was separated by melting it. The resulting liquid was then boiled. Figure 5 presents a particulate representation of this last process. Which of the different particulate representations best represents the final sample? Justify your selection.
6. On Earth, ethane and methane are naturally found as gases and are slightly soluble in water. Figure 3 shows microscopic pictures of a mixture ethane with water and methane with water at 1 atm and 290 K. According to this diagram, which substance is more soluble in water? Use the particulate model of matter to build a hypothesis about the differences in solubility for these two substances.
7. Based on the analysis of all of your answers and the information provided, build a particulate representation of a cross section of Titan, including the different elements and compounds present in its atmosphere, hydrosphere, and bottom of the hydrosphere, and their expected states of matter.

forces based on differences in charge distribution in a molecule (Unit 3).

Level 4: Predicts differences in physical properties based on analysis of molecular structure and charge distribution (Unit 3).

We have used these types of learning progressions as a framework for developing assessment tools to monitor students' level of understanding of targeted concepts and ideas at different points throughout the curriculum. Our goal has been to help students build their understandings in a progressive way, rather than in encapsulated units as it is common in the traditional curriculum.

3. Learning experiences

The types of learning goals, ideas, and objectives described in the previous subsections were used to select, adapt, or design the learning experiences that would help students achieve the desired understandings. Educational research on how people learn (Bransford *et al*., 2000) suggests using a learning cycle (Lawson *et al*., 1989) as instructional model to effectively engage students' interests and prior knowledge, and to promote conceptual understanding. Thus, our course modules have been designed to include a spiral of exploration, term-introduction, and application phases. Given our needs for implementing the curriculum in a large classroom setting, many of the course activities require students working in pairs during lecture time, or in small groups of up to four people in the laboratory. For this purpose, we found it convenient to adopt and adapt many of the pedagogical ideas developed in the context of the guided inquiry POGIL project (Moog and Spencer, 2008), as well as to implement the Science Writing Heuristic as a guide for students' laboratory work (Burke *et al*., 2006).

Group activities in the classroom, called 'Let's Think' in our project, involve students in making observations, identifying patterns, exploring and building models, making predictions and decisions, and constructing explanations (*e.g.*, deciding whether the combustion of glucose will produce more energy per molecule than that of oleic acid based on their chemical structure; building an atomic model to explain provided experimental data; designing two liquid lubricants with different viscosities). Our 'Let's Think' activities have multiple educational purposes: assessing students' prior knowledge (diagnostic) or current understanding (formative), engaging their interest and attention, offering opportunities for exploration and modeling, developing or applying ideas and skills. For these tasks, we frequently rely on a variety of interactive, on-line visualization tools developed to support student learning in the chemistry classroom (Pollard and Talanquer, 2005; Chiu and Wu, 2009). These highly innovative tools create opportunities for students to create their own molecular representations, animations, and simulations, explore the dynamic behavior of chemical systems, and collect and analyze data in real time. They help students build connections between the experiences, theoretical models, and visual representations that are commonly used in chemistry, a skill that educational research has shown is crucial for developing meaningful understandings in the discipline (Gilbert and Treagust, 2009).

Besides the 'Let's Think' activities that are used to target specific concepts and ideas in the classroom, we have also developed educational tasks to help students integrate their knowledge at the end of each course unit. In what we call 'Are You Ready?' assignments, students work in small groups analyzing a system or solving a realistic problem that requires them to apply the central concepts, ideas, and skills developed in a particular course unit. For example, at the end of Unit 2, students are presented with information about a car accident caused by a person driving under the influence of an unidentified drug. Their task is to identify and characterize this substance given the available data (*e.g*. elemental composition, MS and IR spectra, melting point), from determining their structural formula and molecular geometry, to analyzing its narcoleptic effects by comparing its chemical structure with that of other known drugs. During this activity, students have opportunities to share their knowledge about molecular structure and polarity with their classmates (core concepts in Unit 2), receive feedback from the instructor, teacher assistants, and peer tutors, and self-evaluate the extent to which they have attained the outlined learning goals.

Experimental work in the *Chemistry XXI* laboratory is also structured around a set of challenges that students have to collaboratively face and solve in different lab sessions. For example, they may be asked to imagine that they work for a recycling company interested in finding the identity of unknown plastics by simple physical methods, or that they are part of a team from the US Food and Drug Administration charged with monitoring the concentration of food coloring in common power beverages. Experiments are designed for students not only to apply, but to deepen and expand their understanding of the intellectual and practical tools that modern chemists use to analyze, synthesize, transform, and model chemical substances that play important roles in our daily lives. Based on the Science Writing Heuristic approach (Burke, *et al*., 2006), lab activities require students to develop their own plans to face the challenge, identify, collect and analyze relevant data for the task at hand, clearly relate their claims to the experimental evidence, and exchange, discuss, and communicate ideas in effective ways.

Curriculum testing and assessment

The *Chemistry XXI* curriculum has been, and continues to be, developed, tested, and assessed in a sequence of steps. During the first year of the project (in 2007), most of the efforts were focused on the identification, selection, and design of the major threads and core components of the new curriculum. Some of the proposed activities were informally tested in traditional General Chemistry classes taught by the project leaders, using the results of these trials to inform the development process. Detailed course notes, in-class activities, formative and summative assessments, and homework assignments were prepared or outlined during this period. In the fall of 2008, the first blueprint of the full curriculum was pilot-tested in a course section taught by one of the authors of this communication. This pilot test was approved by the Human Subjects committee at our University and all of the students enrolled in the targeted class consented to participate in the project. This allowed us to collect project assessment data in the form of classroom and laboratory observations, questionnaires, surveys, and individual interviews.

The analysis of the assessment data led us to modify different components of the curriculum, from the original sequence of course units, to the approach to the exploration or discussion of some concepts and ideas, to the nature of several of the proposed in-class activities, homework assignments, and course assessments. For example, classroom observations revealed that some of the proposed in-class activities failed to engage people in productive discussions, promoted lower levels of thinking, or were too challenging for most students. In other cases, particularly in those tasks that required the use of interactive simulations to explore the behavior of a given system, students often required more preparation, time, and guidance than we had anticipated. The new focus and structure of the experimental activities, which now granted students the freedom to design their own strategies to solve a problem, were challenging to manage for many of our teaching assistants (TAs) who were used to more traditional lab formats. This led us to restructure the training program for our TAs.

The majority of the students responded positively to the new curriculum, but many of them found it challenging, as illustrated by the following excerpts from a course exit survey:

> *"The class is very conceptual and looks very in-depth at everything you learn. The class is very interactive with a lot of in-class activities. You talk a lot about real world applications of chemistry, you have to apply concepts a lot and not just memorize facts and equations."*
>
> *"Chem XXI taught us how to observe and learn about the world by using chemical thinking. This course was extremely conceptual which is why at times it was very difficult."*
>
> *"A very challenging course because it causes you to think and apply what you learn. This course tries to relate chemistry to the real world and things you may encounter on an everyday basis."*

These comments reflect what we identified as the average student perception of the course; they thought of it as highly conceptual, interactive, and applicable, but intellectually challenging and demanding. We think that this latter perception was in part due to students' lack of exposure to science courses with a strong emphasis on conceptual understanding, rather than algorithmic problem solving. However, these comments made us recognize the need to better scaffold student learning in the course. Unfortunately, during the first pilot-testing of the *Chemistry XXI* curriculum we did not have a textbook or a set of readings tailored to the specific content and structure of the course, which were certainly needed to support student work.

During the first pilot-testing of the curriculum we also compared students' performance in an ACS standardized test at the end of the first semester (n_1 = 239) with that of an equivalent group of students enrolled in a traditional General Chemistry section taught by the same instructor (n_2 = 278). Although ACS exams are designed to measure basic knowledge and problem-solving skills valued in the traditional curriculum, we were interested in comparing students' performance in conventional questions or problems related to topics discussed in our new approach. This analysis revealed no significant difference between the cumulative averages for the selected questions (t = 0.28, p=0.78). This comparison suggested that students involved in the *Chemistry XXI* project performed at the same level as their counterparts in the traditional section, despite the lack of specific training in many of the skills targeted by the ACS exam.

In the fall of 2009 we began the second pilot-testing of the revised curriculum, which is being implemented in two course sections at our university and two additional sections in a nearby community college with a large proportion of part-time students (>60%) from underrepresented minorities in the US. Project assessment tools similar to those already described are in place to collect data that will allow us to fine tune the curriculum and adapt it to better satisfy the needs of diverse classroom settings and student populations. We have also developed an assessment instrument to measure the progress of student conceptual understanding in core areas, which is being applied to both traditional and reformed General Chemistry sections at our university at different points throughout the semester. We expect this instrument to provide more valid and reliable data on the impact of the project on fostering the type of learning that we value, as well as help us compare how core understandings progress in the two types of courses.

It is clear that modern Chemistry is not about balancing chemical equations, solving stoichiometry problems, building electron configurations, or writing Lewis structures. Chemistry is a quest for revealing the identity of substances, understanding diversity in the material and biological world, explaining similarities and differences, transforming nature, and creating what many may consider impossible (Hoffmann, 1995; NRC, 2003). Beyond all the knowledge we have accumulated in the past three hundred years − beyond the multiple applications and relevance of Chemistry in modern society, which certainly students must recognize, understand, and appreciate − our discipline provides a very powerful way of looking and thinking about the world. *Chemistry XXI* thus relies on the firm belief that it is the way chemists think, build and use models, represent systems and processes, design experiments, generate explanations, and approach relevant problems, that we should aspire for our science and engineering majors to understand. According to the existing evidence on student learning and research-based recommendations for chemistry curriculum development (Mbajiorgu and Reid, 2006), these are the types of knowledge and skills that college science students are likely to find useful in their future studies and profession.

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References

American Chemical Society (ACS), (2000), *Chemistry in context: applying chemistry to society,* 3rd Edition, Dubuque, IA: McGraw Hill.

American Chemical Society (ACS), (2001), *Chemistry in the community (ChemCom)*, 4th Edition, New York, NY: W. H. Freeman.

American Chemical Society (ACS), (2005), *Chemistry,* New York, NY: W. H. Freeman.

Anthony S., Mernitz H., Spencer B., Gutwill J., Kegley S., and Molinaro M., (1998), The ChemLinks and ModularCHEM consortia: using active and context-based learning to teach students how chemistry is actually done, *J. Chem. Educ.*, **75**, 322-324.

Barker V., (2000), *Beyond appearances: students' misconceptions about basic chemical ideas,* Royal Society of Chemistry: London.

Bennett J. and Lubben F., (2006), Context-based chemistry: the Salters approach, *Int. J. Sci. Educ.*, **28**, 999-1015.

Bodner G. M., (1992), Why changing the curriculum may not be enough? *J. Chem. Educ.,* **69**, 186-190.

Bransford J. D., Brown A. L. and Cocking R. R., (eds.), (2000), *How people learn: brain, mind, experience, and school,* Washington DC: National Academy Press.

Burke K. A., Greenbowe T. J., Lewis E. and Peace E., (2002), The Multi-Initiative Dissemination Project: strategies for active student learning, *J. Chem. Educ.,* **79**, 699-?.

Burke K. A., Greenbowe T. J. and Gelder J. I., (2004), The Multi-Initiative Dissemination Project workshops: who attends them and how effective are they? *J. Chem. Educ.,* **81**, 897-902.

Burke K. A., Greenbowe T. J., and Hand B. M., (2006), Implementing the Science Writing Heuristic in the chemistry laboratory, *J. Chem. Educ.,* **83**, 1032-1038.

Chiu M. H., and Wu H.-K., (2009), Ways forward: eliciting students' mental models and exploring multimedia in science learning, in J. Gilbert and D. Treagust (eds.), *Multiple representations in chemical education*, New York: Springer.

Claesgens J., Scalise K., Wilson M. and Stacy A., (2009), Mapping student understanding in chemistry: the perspectives of chemists, *Sci. Educ.*, **93**, 56-85.

Eĝe S. N., Coppola B. P. and Lawton G., (1997), The University of Michigan undergraduate chemistry curriculum. 1. Philosophy, curriculum, and the nature of change, *J. Chem. Educ.,* **74,** 74-83.

Evans K. L., Leinhardt G., Karabinos M. and Yaron D., (2006), Chemistry in the field and chemistry in the classroom: a cognitive disconnect, *J. Chem. Educ.,* **83**, 655-661.

Gabel D. L. and Bunce D. M., (1994), Research on problem solving: chemistry, in D. L. Gabel (ed.), *Handbook of research in science teaching and learning,* New York: Macmillan and the National Science Teacher Association, pp. 301-326.

Gilbert J. K. and Treagust D. (eds.), (2009), *Multiple representations in chemical education*, The Netherlands: Springer.

Gillespie R. J., (1991), What is wrong with the general chemistry course? *J. Chem. Educ.,* **68**, 192-194.

Gillespie R. J., (1997), Reforming the general chemistry textbook, *J. Chem. Educ.,* **74**, 484-485.

Gutwill-Wise J. P., (2001), The impact of active and context-based learning in introductory chemistry courses: an early evaluation of the modular approach, *J. Chem. Educ.,* **78**, 684-690.

Hawkes S. J., (2005), Introductory chemistry needs a revolution, *J. Chem. Educ.*, **82**, 1615-1616.

Hoffmann R., (1995), *The same and not the same*, New York: Columbia University Press.

Landis C. R., Peace G. E., Scharberg M. A., Branz S., Spencer J. N., Ricci R. W., Zumdahl S. A. and Shaw D., (1998), The New Traditions Consortium: shifting from a faculty-centered paradigm to a student-centered paradigm, *J. Chem. Educ.,* **75**, 741-744.

Lawson A. E., Abraham M. R. and Renner J. W., (1989), *A theory of instruction: using the learning cycle to teach science concepts and thinking skills* [Monograph, Number One], Kansas State University, Manhattan, Kansas: NARST.

Lloyd B. W., (1992a), A review of curricular changes in the general chemistry course during the twentieth century, *J. Chem. Educ.,* **69**, 633-636.

Lloyd B. W. (1992b), The 20th century general chemistry laboratory, *J. Chem. Educ.,* **69**, 866-869.

Lloyd B. W. and Spencer J. N., (1994), New directions for general chemistry, *J. Chem. Educ.,* **71**, 206-209.

Mbajiorgu N., and Reid N., (2006), *Factors influencing curriculum development in chemistry: a physical sciences practice guide*, Hull, United Kingdom: Higher Education Academy of Physical Sciences Centre.

Moog R. S., and Spencer J. N., (2008), *POGIL: Process Oriented Guided Inquiry Learning,* Oxford University Press: New York.

Nakhleh M. B., (1992), Why some students don't learn chemistry, *J. Chem. Educ.,* **69**, 191-196.

National Research Council (NRC), (2001), *Knowing what students know: the science and design of educational assessment,* Washington DC: National Academy Press.

National Research Council (NRC), (2003), *Beyond the molecular frontier: challenges for chemistry and chemical engineering,* Washington, DC: National Academy Press.

Nowak-Thompson B., (2005), Introducing GC/MS into the first-year General Chemistry curriculum using pattern recognition and a verbal analogy, *Chem. Educator*, **10**, 179-180.

Nurrenbern S. C. and Pickering M., (1987), Concept learning versus problem solving: is there a difference? *J. Chem. Educ.,* **64**, 508-511.

Pollard J. and Talanquer V., (2005), Interactive digital overheads: dynamic teaching tools for the chemistry classroom, *Chem. Educator*, **10**, 36-40.

Reid N., (2000), The presentation of chemistry logically driven or applications-led, *Chem. Educ. Res. Pract.*, **1**, 381-392.

Schwartz A. T., Bunce D. M., Silberman R. G., Stanitski C. L., Stratton W. J. and Zipp A. P., (1994), Chemistry in context: weaving the web, *J. Chem. Educ.,* **71**, 1041-1044.

Schwartz A. T., (2006), Contextualized chemistry education: the American experience, *Int. J. Sci. Educ.*, **28**, 977-998.

Spector T. L., (1994), Using infrared spectroscopy for the curricular integration of general and organic chemistry, *J. Chem. Educ.,* **71**, 946-947.

Spencer J. N., (1992), General chemistry course content, *J. Chem. Educ.,* **69**, 182-186.

Taber K., (2002), *Chemical misconceptions – prevention, diagnosis and cure. Vol I: theoretical background,* Royal Society of Chemistry: London.

Talanquer V., (2006), Common sense chemistry: a model for understanding students' alternative conceptions, *J. Chem. Educ.,* **83**, 811-816.

Talanquer V., (2009), On cognitive constraints and learning progressions. The case of "structure of matter," *Int. J. Sci. Educ.,* **31**, 2123-2136.

Wiggins G., and McTighe J., (1998), *Understanding by design*, Upper Saddle River, NJ: Merrill/Prentice Hall.

Wilson M., and Scalise K., (2006), Assessment to improve learning in higher education: the BEAR assessment system, *High. Educ.,* **52**, 635-663.

Wilson M., (2009), Measuring progression: assessment structures underlying a learning progression, *J. Res. Sci. Teach.,* **46**, 716-730.