Chemistry Education: Ten Dichotomies We Live By

Vicente Talanquer
Department of Chemistry and Biochemistry, University of Arizona. Tucson, AZ 85721
E-mail: vicente@u.arizona.edu

Abstract
Modern thought in chemical education seems to be shaped by a set of dichotomies that are useful in indentifying and highlighting problems, as well as in generating and communicating novel ideas. However, these binary oppositions may also constrain our thinking. Among these dichotomies, we draw attention to ten different oppositions including, among others, the pairs Abstract/Concrete, Algorithmic/Conceptual, and Symbolic/Microscopic. The central goal of this contribution is to reflect upon the scope and limitations of common dichotomic conceptualizations of critical elements of chemical education. Our major motivation is to invite chemical educators to critically analyze ideas or beliefs that we often take for granted.

Keywords: General Public, Chemical Education, Teaching/Learning,

Introduction
For historical, philosophical and maybe psychological reasons, chemistry is a science built upon a wide variety of dichotomic concepts such as Acid/Base, Oxidation/Reduction, Ionic/Covalent, Nucleophile/ Electrophile, and Exothermic/Endothermic.1 Although chemists recognize the limitations of these types of binary oppositions, we commonly generate explanations based on either the confrontation between these opposites or by highlighting their complementary properties and behaviors: Strong acids versus weak bases; strong reducers versus weak oxidizers.2 We also frequently explain chemical processes as driven by the tension between opposite poles: Stable versus unstable, inert versus labile, substrate versus reagent, static versus dynamic. It is through the battle of opposites, or by invoking the balance between complementary wants and needs, that we often make sense of chemical change or justify the properties of chemical substances.

The way we talk about chemical substances and processes in daily life is also full of dichotomies. For example, we recognize natural and artificial materials, we refer to pure and impure substances, and we discuss the costs and benefits of chemical products. Public perceptions of chemistry, the chemical industry and their products are also shaped by opposite dualities such as beneficial and harmful, clean and polluting, or safe and dangerous.3 It is likely that no other literary character embodies the social perception of Chemistry better than Dr. Jekyll and Mr. Hyde, a dual character, the angel and the demon.4 Nobel Prize winner Roald Hoffmann has claimed that the constant tension between opposites is precisely what makes chemistry such a vibrant, interesting, vital, and human science.5 Chemist and writer Pierre Laszlo sees the duality and circularity of many chemistry concepts as a source of vitality and dynamism in chemical thought, but also points out that the plethora of complementary and circular ideas in our discipline may be partly responsible for student difficulties in understanding the subject.2

I would like to suggest that thinking in dichotomic terms about important learning and teaching issues also comes natural to many chemical educators. Describing and analyzing educational agents and phenomena in terms of binary oppositions resonates well with us and often facilitates the identification of educational problems, as well as the generation and communication of novel ideas. However, as is the case with many chemical dichotomies, framing problems in terms of extreme opposites sometimes leads us to think in narrow terms and to ignore the many shades of gray that are characteristic of the actions, reasoning, and attitudes of chemistry teachers and students. Thus, the central goal of this paper is to highlight, characterize, and reflect upon the scope and limitations of ten different dichotomies that have shaped thinking in chemical education in recent years. The major motivation for this work is to invite chemistry educators, particularly prospective and novice chemistry teachers, to critically analyze ideas or beliefs that often we take for granted. The ten dichotomies are presented looking to first highlight interconnected issues in the learning of chemistry followed by closely related ideas in the teaching of the discipline.

Abstract versus Concrete
Dudley Herron’s paper “Piaget for Chemists” is regarded as one of the most influential papers in the existing literature in chemical education of the last fifty years.6 This work advanced the hypothesis that many of our students’ difficulties in understanding chemistry are due to their lack of development of formal (versus concrete) thought. Based on Piaget’s ideas about intellectual development,6 it was suggested that many college chemistry students are at the concrete operational stage in
their reasoning ability, unable to understand abstract concepts that depart from concrete reality. Herron’s ideas brought the Abstract versus Concrete dichotomy of chemical concepts and procedures to the forefront of the discussions in chemical education. To some extent, the paper opened the door to the widespread belief that chemistry is difficult because we ask students to think about too many abstract entities that they cannot see or touch. But to what extent is this true?

Some of Piaget’s ideas about intellectual development have been challenged in recent years, particularly the assumption that human reasoning evolves through well defined age-related stages. Nevertheless, there is ample evidence that suggests that many of our college students are unable to think at the formal level when facing a variety of questions or problems. If this is the case, what makes these problems difficult for the students? Is it the level of abstraction of the actual entities students are asked to think about, for example molecules versus actual substances, or energy versus actual temperature changes? Or is it rather the type of reasoning that is demanded from them independently of the abstract/concrete nature of the concepts involved? Although it is possible that both the nature of the concepts and the type of reasoning influence students’ performance, recent educational research questions the building of a direct link between level of abstraction and level of difficulty. Thinking with or about concrete objects or events may be as simple or as challenging as reasoning involving abstract entities. From this perspective, chemistry may not be difficult because of the nature of the things we talk about but rather because of the high cognitive demand of the questions and problems we pose, which in many cases require making judgments and decisions taking into account the effect of multiple factors, both concrete and abstract.

Submicroscopic versus Symbolic
The idea advanced by Alex Johnstone that chemical knowledge can be represented in three main ways: Macro, submicro, and symbolic has become paradigmatic in chemical education. This “chemistry triplet” now serves as a framework for the development of textbooks, curriculum materials, and research projects in chemical education. Although the triplet represents chemical knowledge as a trichotomy, research on students’ naïve misconceptions has been enormous in many different areas of science education. In the case of chemistry, this research has uncovered a wide variety of alternative ideas that students may have in almost every topic addressed in their science classes. Research in chemical education has shown that students seem to develop the latter ability to a certain extent while failing to understand the underlying models that give meaning to chemical symbols.

The submicroscopic/symbolic opposition has opened our eyes to the shortcomings of teaching approaches that focus too much on the manipulation of symbols to the detriment of the meaningful analysis and discussion of the associated models of matter. However, distinguishing between the world of symbols and the world of models is not always easy. For example, many chemical representations are hybrids in the sense that they include symbolic elements combined with iconic components that seek to model properties of a system (e.g., a wedge-dash representation of a molecule conveying symbolic information about composition but also presenting modeling cues about geometry). Where do the symbols end and the models begin? In drawing a chemical reaction using particulate representations of matter instead of chemical formulas one may claim that the chemical model is made more explicit. However, we are still relying on a symbolic system that captures only a few of the critical elements of the actual chemical model of chemical reactions. Perhaps the core of the issue is not so much that we need to help students to connect the symbolic and the submicroscopic representations we use, but that we need to foster their ability to generate mechanistic explanations that account for experimental data or that productively model the behavior of a system, independently of the symbols they use to represent ideas.

Misconceptions versus Scientific Conceptions
The influence of research studies on students’ misconceptions has been enormous in many different areas of science education. In the case of chemistry, this research has uncovered a wide variety of alternative ideas that students may have in almost every topic addressed in our curricula: Atomic and molecular structure, chemical bonding, chemical equilibrium, acids and bases, thermochemistry, kinetics. Results from these studies have shown that students come to our chemistry classes with many preconceived ideas about the nature and properties of matter, and that unfortunately many of them leave our courses without fully comprehending the scientific concepts and ideas that we want them to learn. By highlighting the Misconceptions versus Scientific Conceptions dichotomy, research on students’ naïve beliefs has exposed both the limitations that traditional methods of teaching have in promoting conceptual understanding as well as the major challenges that instructors face in fostering conceptual change.
Although the misconceptions versus scientific conceptions opposition has helped us recognize the critical importance of eliciting and challenging students’ ideas in the classroom, this dichotomic view of student knowledge and understanding has been criticized on various fronts. Some educators consider, for example, that classifying students’ alternatives conceptions as misconceptions leads us to quickly dismiss them as incorrect ideas instead of using them as productive resources for building understanding. Instructors also often talk of misconceptions as more or less fixed and coherent ideas that need to be replaced by scientific understandings. However, educational research suggests that students’ ideas are somewhat fragmented and pretty dynamic, and thus may vary from task to task. From this perspective, the actual misconception may be difficult to identify. It has also been suggested that students’ misconceptions in chemistry are just the surface manifestation of implicit assumptions about the nature and behavior of matter. Thus, focusing on dispelling specific misconceptions (e.g., water molecules break apart during boiling; copper atoms are shiny) may be rather unproductive if the underlying ways of reasoning are not elicited, reflected upon, and challenged.

Algorithmic versus Conceptual
The seminal work by Nurrenbern and Pickering on concept learning versus problem solving highlighted the shortcomings of the quantitative approach to chemistry teaching. Their ideas set the basis for what has become a powerful dichotomic classification, the Algorithmic versus Conceptual opposition, of not only chemistry questions and problems but also approaches to teaching the discipline. In general, algorithmic questions or approaches are characterized as requiring or emphasizing memorized set of procedures to find solutions, while conceptual problems or ways of teaching are seen as requiring students to meaningfully apply core concepts and ideas. The recognition of these opposite approaches to questioning, problem-solving, and teaching has been extremely productive in chemistry education as it has forced us to reflect on the types of reasoning that we actually promote in our classrooms.

Although thinking of chemistry problems as algorithmic or conceptual may be useful for planning and assessment purposes, one should recognize that making the distinction between these two types of problems may be more complex than it seems. For example, one may argue that what makes many questions algorithmic or conceptual is not their actual content but rather the way in which teachers and students frame the problems and approach their solution. For example, many instructors tend to think of questions that involve conversions between particulate (or submicroscopic) and symbolic representations of a substance or process as conceptual problems. However, many students approach these types of questions in rather algorithmic ways. Similarly, there are problems that experts could solve using a set of well established algorithms or heuristics but may demand a high level of conceptual understanding from the novices in the field. Thus problem framing and level of expertise may fool our expectations for the type of reasoning that a question may trigger, blurring the boundary between the application of concepts and memorized routines.

Memorization versus Understanding
Perhaps no other dichotomy is more frequently used in modern times to differentiate good from bad teaching than the contrast between Memorization and Understanding. This dichotomy is often linked with two contrasting teaching approaches, one emphasizing the memorization of facts and the other stressing the understanding of concepts. The opposition between memorization and understanding, or between facts and concepts, has sparked healthy debates about both the content of conventional chemistry curricula and the effectiveness of traditional teaching practices. However, it has sometimes hindered communication between chemical educators with different perspectives on what is needed and what is feasible in the teaching of chemistry, particularly at the introductory levels.

It is likely that all chemistry teachers and instructors want their students to understand what they see as the central concepts and ideas that they teach. To claim that traditional chemistry teachers value memorization over understanding is to fail to acknowledge the complexity of teacher thinking. I suspect that the dilemma that many teachers face is based on the implicit or explicit recognition that meaningful understanding demands a wide and strongly interconnected knowledge base. Thus, some instructors believe that this knowledge base needs to be built first, before engaging students with more cognitively complex tasks that otherwise they would fail. Other instructors consider that the knowledge base can be created on a need-to-know basis as students actively engage in high-level reasoning activities, such as building models, generating arguments, and constructing explanations on selected topics. Research evidence suggests that this latter approach is more likely to promote conceptual understanding of targeted ideas, while the former teaching practices tend to foster the development of a wider but more fragile and fragmented knowledge base.

Breadth versus Depth
The issue of depth versus breadth has been at the center of all major science curriculum reforms of the past fifty years. Breadth of the curriculum is often defined in terms of the number of topics or concepts that are covered. The definition of depth of the curriculum is somewhat more vague. Sometimes depth is interpreted as a larger quantity of knowledge about certain topic, while
in some cases the term is used to refer to the opportunities that the curriculum creates for students to develop an integrated understanding of the central ideas that are targeted. In the case of chemical education, discussions about Breadth versus Depth have been critical in sparking important curriculum reform initiatives for introductory chemistry courses. However, this dichotomy has also often obscured important debates between chemical educators.

The breadth versus depth dichotomy highlights the common belief that a curriculum is either deep or broad. From this perspective, depth can only be achieved at the expense of breadth, which is likely true given the time limitations in any course. However, the dichotomy also seems to imply that a curriculum that addresses fewer topics has a higher degree of depth, which is not necessarily the case. For some instructors, going deeper into a topic means to introduce the more advanced, accurate, or mathematically sophisticated models and theories about a system of interest (e.g., atomic structure, chemical bonding). Unfortunately, this increase in disciplinary depth may not translate into deeper conceptual understanding. For other instructors, going deeper means the creation of opportunities for students to apply a fundamental idea or way of thinking in a variety of situations or contexts. Evidence suggests that this latter approach is likely to lead to more meaningful learning, but not necessarily to more sophisticated understandings. Thus, although many chemistry instructors may agree with the idea of increasing the depth of the curriculum, they may be talking about rather different things.

Rigor versus Relevance

The development of curriculum initiatives such as Chemistry in Community (ChemCom), Salters Chemistry, and Chemistry in Context reflects the strong belief of some chemical educators in the importance of teaching chemistry in ways that are relevant to all students. However, the frequent marginalization of many of these curriculum initiatives to courses deemed only appropriate for students who are not college-bound or who are not planning to pursue a career in science or engineering is indicative of another important dichotomy we seem to live by, the opposition between Rigor and Relevance.

All chemistry instructors recognize the central role that chemistry plays in modern society and the variety of relevant applications that chemistry concepts and ideas have in daily life. Nevertheless, many of them consider that centering chemistry courses on the analysis and discussion of these relevant topics will decrease their academic rigor. This judgment is in part based on the belief that most relevant problems or applications are so complex that their study can only be approached in a descriptive manner in introductory courses. Additionally, it is argued that in order to understand relevant problems in a meaningful way, a solid knowledge base is first required. Escaping the rigor versus relevance dichotomy may be difficult but not necessarily impossible. I would claim that relevance can be put at the center of our chemistry courses without losing rigor if we shift our attention from teaching what we know about relevant systems to teaching how we apply chemical thinking to solve relevant problems. Context-based courses help students understand the chemistry behind critical issues in our world, such as global warming or alternative energy sources. Without losing the relevance, we could design rigorous courses that help students develop the type of thinking that we use to answer critical questions such as how do we know what is in our surroundings? or how do we harness chemical energy?

Lecture versus Laboratory

Although many chemists think of their discipline as a science that integrates theory and practice, the teaching of the discipline is, particularly at the college level, sharply divided into the Lecture versus Laboratory experiences. The division between lecture and laboratory is not only determined by what students are asked to do, but also by what they are asked to think about in each of these environments. Lectures are often focused on the description and analysis of models and theories, the presentation and discussion of explanations, and the development of skills in quantitative problem-solving. Laboratories are conceived as spaces for doing observations, collecting and analyzing data, and developing manipulative skills; they are also often seen as opportunities for verification of principles and theories discussed in lectures. Many chemical educators strive to align lectures and labs to show the correlation between ideas and experiments. However, their efforts are frequently only partially successful due to many practical limitations.

The dichotomy lecture/laboratory is based on the assumption that there are different types of knowledge and skills that can be best developed in each of these environments. However, this is a rather constraining assumption. Why could lectures not be spaces where students engage in the collection and analysis of data generated via, for example, computer simulations? Why is it that laboratories could not be more focused on the development of models, generation of arguments, and construction of explanations? The current opposition in the conceptualization of lecture and laboratory work hinders students’ opportunities to develop intellectual skills that most instructors highly value. Why is it that collaborative group work is seen as natural in the laboratory but not in the lecture? Why is it that student initiative and creativity is so much valued in the laboratory setting but not in the classroom? Why is it that we seek high intellectual engagement in our lectures but...
we are comfortable with our students spending hours on routine experimental manipulations? From my perspective, concerns about alignment between lecture and lab are somewhat misguided. The critical issue is not so much that lecture and lab do not follow each other in terms of content, but that these two learning spaces are far too divorced in their intellectual goals.

**Verification versus Inquiry**

Questions about the effectiveness of traditional laboratory instruction at the secondary and college levels have prompted a strong reform movement centered on the idea of “inquiry.”35 Although the term inquiry teaching may be interpreted in different ways, it often refers to creating opportunities for students to generate and evaluate scientific explanations of the natural world, and to participate in scientific practices and discourse. Inquiry labs are frequently defined in opposition to the so-called verification labs in which students are asked to follow a set of well-defined procedures to test a scientific prediction or to verify an expected result. This dichotomy tends to create or reinforce some misconceptions. For example, the idea that inquiry labs always require that students take full control of their investigations or that verification labs should be avoided at any cost.

One of the problems with the dichotomic view of chemistry labs is that it ignores that there could be experiments with different degrees of inquiry. The inquiry level is determined by the extent to which students take ownership in the design of different parts of an investigation. For example, several educators distinguish between structured, guided, and open inquiry labs based on a rubric that analyzes students’ direct involvement in different science practices such as generating research questions, designing experiments, and developing strategies to analyze data.36 Educational research has shown that student engagement in inquiry-based investigations has a positive impact on learning when properly scaffolded.37 This scaffolding is often accomplished by engaging students in sets of investigations with progressively higher levels of inquiry. As part of this scaffolding, verification labs could play a critical role in helping students develop specific skills. Thus, the opposition between verification and open inquiry labs should not be seen as a question of “either/or” but rather as a matter of “when and for what purpose.”

**Teacher-Centered versus Student-Centered**

The last dichotomy I would like to address is potentially the most divisive of all. It characterizes our teaching as either Teacher-Centered or Student-Centered. This binary opposition is often used to create contrast between tradition and innovation in teaching, between passive and active learning, and between belief-based and research-based approaches to teaching.38 This dichotomy is sometimes invoked to portray teaching and learning as either fully designed and controlled by the instructor or fully determined by the interests, desires, and wishes of the learner. Which of these two extremes is judged to be best depends on the personal beliefs of the person making the argument. Many instructors recognize the potential advantages of learning environments in which students take more ownership of their learning. However, many teachers resist abandoning their teacher-centered practices because of perceived curricular pressures (e.g., too much material to cover), personal beliefs about how people learn, lack of planning time, or lack of knowledge about how to implement productive and effective student-centered activities.

There is ample evidence of the positive effects on learning and achievement of student-centered environments in which students are invited to explore ideas, engage in argumentation, and build models and explanations while working in collaborative small groups; encouraging self-monitoring and self-assessment seem also to be crucial.25,26 However, the same evidence suggests that these activities have to be carefully planned, orchestrated, and formatively assessed by teachers. The fact is that there is not much student-centered learning without careful teacher-centered planning and feedback. One of the most problematic aspects of the teacher-centered/student-centered dichotomy is that it is often used to dismiss the work of instructors in either side of the divide, by either oversimplifying the goals and beliefs of traditional instructors (e.g., they want students to memorize facts, they think students’ minds are blank slates, they don’t care about student understanding, they think students who fail are lazy or dumb) or misrepresenting the ideas and goals of instructors who seek to more actively involve students in their learning (e.g., they think students know what they need to learn, they think students’ ideas are as valuable as scientific understandings, they think students can build sophisticated scientific ideas on their own, they water down the curriculum and waste their time). In this regard, everybody would benefit from more open and frequent discussions about these issues, and by conceding each other the benefit of the doubt.

**Final Comments**

The set of ten dichotomies described and discussed in this paper is not conceived to be complete or exhaustive. Neither do I claim that all of these dichotomies are equally relevant in all contexts or that they only affect the way of thinking of chemical educators. The main argument that I would like to advance is that dichotomic thinking in chemical education is productive in some ways but constraining in others. As educators, we have the
responsibility to carefully and critically analyze our knowledge and beliefs about learning and teaching. Dichotomies are powerful because painting the world in black and white helps us recognize major differences and simplify the analysis of complex systems. However, we should not forget that reality is likely to be more colorful and diverse. As chemists, we know this to be true; let’s not forget it as chemical educators.

References
33. Talanquer, V. Sci. & Educ. 2011 (Online First).