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# Central Ideas in Chemistry: An Alternative Perspective

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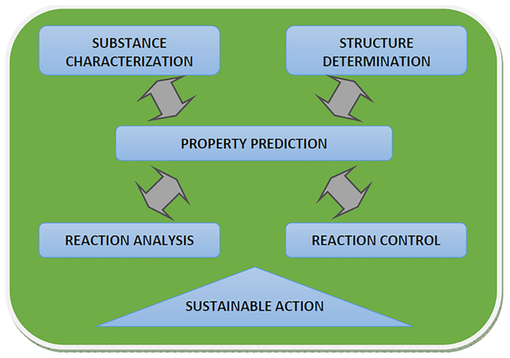
**ABSTRACT:** Central ideas define fundamental understandings in a domain and frame curriculum development, instruction, and assessment. How these central ideas are conceptualized can thus have a major impact on what teachers and instructors do in the classroom and on the understandings that students develop. This commentary presents a reflection on how central ideas are traditionally presented in introductory chemistry courses and suggests an alternative way of framing these understandings to convey a more authentic view of the nature of our discipline.



**KEYWORDS:** *High School/Introductory Chemistry, First-Year Undergraduate/General, Curriculum*

## INTRODUCTION

As chemistry educators, we should constantly reflect on the central concepts and ideas that we want our students to understand, and on the best ways in which such understandings can be developed and demonstrated. However, engaging in critical reflection and action in chemistry education may be challenging in the face of strong traditions on how courses should be taught. In this rather conservative environment, alternative educational perspectives are often marginalized but are sorely needed to motivate discussion and diversify the views of those who approach teaching as an exploration rather than as a prescription.

The major goal of this commentary is thus to provide an alternative perspective on a major issue in chemistry education. Specifically, this is a reflection on how we define and think about central ideas in our discipline. The development of educational standards in the US and across the world in the past 20 years has focused on the identification of central ideas that students at different educational levels are expected to master.[1−5] These central ideas define fundamental understandings in a domain and frame curriculum development, instruction, and assessment. How these central ideas are conceptualized can thus have a major impact on what teachers and instructors do in the classroom and on the understandings that students develop.

## CENTRAL IDEAS IN CHEMISTRY

The concept of "central" or "big" ideas in science education assumes that every scientific domain builds upon a set of key ideas that enable understanding of events and phenomena of relevance in a discipline.[1−6] The reference to central ideas seeks to define the goals of science education not as the acquisition of a body of facts but rather as the development of understandings that have considerable explanatory power, provide the basis for prediction and decision-making in a wide range of relevant contexts, and are intellectually satisfying because they generate the answers to many questions of personal or social interest.[6] These central ideas are seen as critical for basic competency because they serve as building blocks for future and more in-depth science understanding.

Several science and chemistry educators have embarked on the task of identifying and describing central ideas in chemistry. Ronald Gillespie[7] and Peter Atkins,[8,9] for example, independently proposed the set of ideas summarized in the first two columns in Table 1. More recently, the ACS Examination Institute engaged in the identification of a set of anchoring concepts and eduring understandings for the undergraduate chemistry curriculum that nicely summarize central ideas in the discipline (see third column in Table 1).[10,11] Similarly, the College Board has published a set of standards for college success that includes a collection of enduring understandings in chemistry,[12] and comparable ideas can be found in the recent NRC Framework for K-12 Education[3] and the associated Next Generation Science Standards document.[4]

The analysis of the various documents in which central ideas in chemistry have been identified reveals great agreement among different authors. Analogous understandings about the atomic nature of matter, chemical bonding, molecular structure, structure−property relationships, chemical reactions, and reaction energetics and dynamics are described in all cases. These documents state ideas that are unarguably keys to understanding the properties and behavior of matter. Consequently, the goal of this commentary is not to challenge the centrality of any of these ideas, but rather to reflect on what their presentations implicitly tell us about current views of what "chemistry" should be taught in schools and propose an

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Table 1. Summary of Central Ideas in Chemistry Identified by Different Authors

| Ronald Gillespie[7] | Peter Atkins[9] | ACS Examination Institute[10,11] |
|---|---|---|
| 1. Atoms, molecules, and ions are the basic components of matter. | 1. Matter is composed of atoms. | 1. Matter consists of atoms with internal structures that dictate their behavior. |
| 2. Chemical bonds are formed by electrostatic attractions between positively charged cores and negatively charged valence electrons. | 2. Elements form families. | 2. Atoms interact via electrostatic forces to form chemical bonds. |
| 3. Atoms in molecules and crystals arrange in particular geometries. | 3. Bonds form between atoms by sharing electron pairs. | 3. Chemical compounds have geometric structures that influence their chemical and physical behaviors. |
| 4. Atoms and molecules are in constant motion. | 4. Shape is of utmost importance. | 4. Intermolecular forces dictate the physical behavior of matter. |
| 5. Atoms in molecules and crystals can reorganize to form new molecules and crystals. | 5. Molecules interact with one another. | 5. Matter changes, forming products that have new chemical and physical properties. |
| 6. Reactions occur when the disorder of the universe is increased. | 6. Energy is conserved. | 6. Energy is the key currency of chemical reactions in molecular-scale systems as well as macroscopic systems. |
| | 7. Energy and matter tend to disperse. | 7. Chemical changes have a time scale over which they occur. |
| | 8. There are barriers to reactions. | 8. All physical and chemical changes are, in principle, reversible and often reach a state of dynamic equilibrium. |
| | 9. There are only four fundamental types of reaction. | 9. Chemistry is generally advanced via experimental observations. |
| | | 10. Chemistry constructs meaning interchangeably at the particulate and macroscopic levels. |

alternative way of framing these ideas to convey a more authentic view of the nature of our discipline.

## MAIN ISSUES

The central ideas summarized in Table 1 represent core understandings that are useful in describing and explaining the properties of materials and their transformations. Most of these ideas invoke particulate models of matter that have played a transformative role in how scientists think about physical, chemical, and biological systems. They are presented, however, as neutral statements about the nature of chemical entities and processes, devoid of intentionality or practical purpose. They are the foundations of a discipline portrayed as an explanatory science dedicated to making sense of the properties and behavior of matter. This view of chemistry has been dominant in education for many years, particularly in introductory chemistry courses at the secondary school and college levels, despite its shortcomings.[13]

Several authors have argued that the traditional conceptualization of chemistry as an explanatory science fails to capture the different goals and practices of the chemical enterprise.[14−18] In particular, it neglects to recognize that chemical knowledge is often developed for practical purposes, involving the characterization and production of targeted types of matter. Ideas in chemistry are certainly generated seeking to explain and predict properties and behaviors, but also to design, control, and create desired outcomes.[19] Unfortunately, the technoscientific nature of chemistry is erased in dominant school curricula, replaced by an aseptic and unproblematic view of the discipline to fit the mold of a prototypical physical science.[16] Moreover, the excessive focus on molecular-level ideas obscures the fact that chemistry is also a science of macroscopic entities that are manipulated in lab and industrial settings, under the influence of economic, political, social, environmental, and ethical considerations.[20]

It may be argued that the explanatory face of chemistry is the most relevant for students in introductory chemistry courses to engage with. Ultimately, most of these students will not pursue a chemistry-related career and the understandings that they develop in their chemistry classes should be useful in other contexts. These understandings should, for example, allow them to make sense of biological phenomena and environmental systems. This argument, however, ignores that chemical understandings and products are used in other disciplines equally as sources of explanation and prediction as practical tools for analysis, transformation, and control (e.g., drug analysis and design, pollutant detection and elimination). Moreover, individuals in their daily lives are more likely to engage in decision-making related to the consequences of using chemical products and processes than in building chemical explanations about natural phenomena.[21]

## AN ALTERNATIVE PERSPECTIVE

Chemistry is a vast and complex enterprise developed in research laboratories and chemical industries. Its goals are diverse, and its impacts extend far beyond the traditional realms of the pure sciences.[14] One can, however, identify a set of practices in which most chemical scientists engage and a set of essential questions that they seek to answer. Most chemists are in the business of analyzing, transforming, and synthesizing diverse types of matter.[22,23] In their work, they query about: *What is this material made of?* (the question of *Identity*); *How do a material's properties relate to its composition and structure?* (the question of *Structure−Property Relationships*); *Why does a material undergo changes?* (the question of *Causality*); *How do those changes happen?* (the question of *Mechanism*); *How can those changes be controlled?* (the question of *Control*); and *What are the consequences of such changes?* (the question of *Benefits-Costs-Risks*).[18]

The signature of chemistry is less its content than the practices that such knowledge enables. Chemistry is less a body of knowledge than a powerful way of thinking about and acting on the material world. Consequently, central ideas expressed as statements of fundamental knowledge do not suffice to

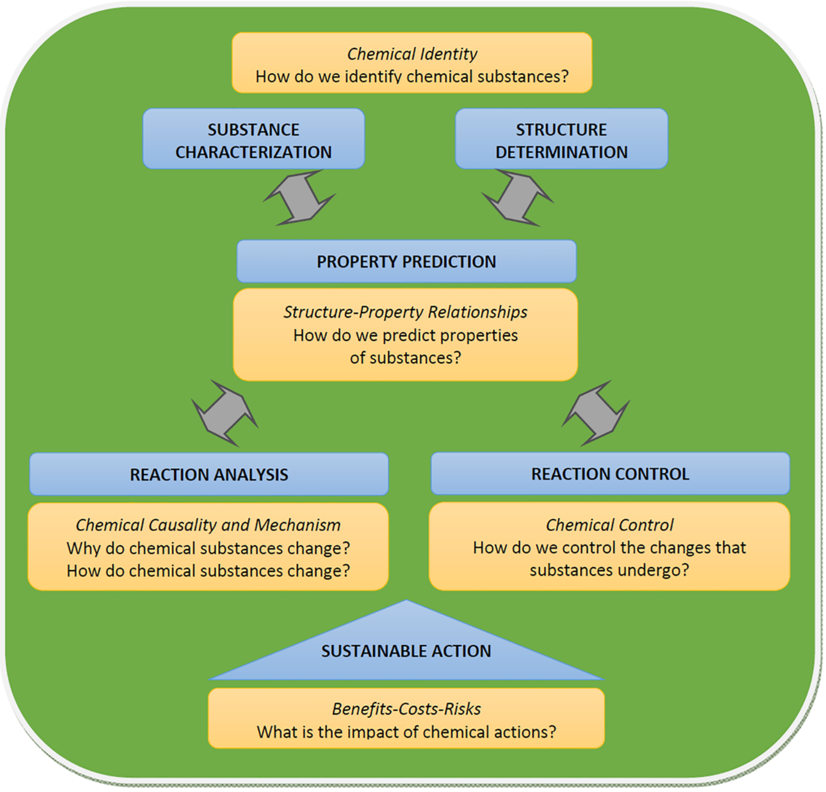

**Figure 1.** Framework for central ideas for practice of chemistry.

characterize our discipline and shortchange its scope and relevance. Central ideas should instead encapsulate the understandings and actions that help address essential questions in chemistry. These central ideas should certainly be tools for explaining targeted properties and behaviors, but also for reflecting and acting on the world for practical purposes. The framework presented in the next paragraphs seeks to achieve such goals.

The proposed framework includes six central ideas organized in three major groups (see Figure 1). These ideas are conceived as "ideas for practice" as they interweave core disciplinary content, practices, and aims of the chemical enterprise. The "foundational" group includes two fundamental ideas for practice (Substance Characterization, Structure Determination) that define and characterize the objects of interest in chemical thinking. The "bridging" group includes three ideas for practice (Property Prediction, Reaction Analysis, Reaction Control) that serve as intellectual and practical guides in understanding and controlling changes in the material world using chemical models. Lastly, the "contextual" group includes an overarching idea (Sustainable Action) that outlines the ideals to which engagement in chemical thinking and action should aspire (chemical ethos).

## Foundational Ideas for Practice

Chemical scientists analyze and transform the material world by modeling it at two different levels, the macroscopic level of tangible materials and a parallel submicroscopic level assumed to underlie the macroscopic material world.[24−27] Exploration at each of these two levels is guided by the following two foundational ideas for practice that define the entities of interest and describe how they are typically characterized. These two ideas summarize how chemical thinking is used to determine the chemical identity of the components of any material system of interest.

**I. Substance Characterization.** Chemical scientists have untangled the complexity of the material world by assuming that all materials are composed of one or more chemical substances, each of them possessing a unique set of physical and chemical properties that distinguish them.[28] These unique sets of differentiating properties can be used to detect the presence of a given substance in a system, separate it from other substances, identify it, and quantify its amount.[29] These differentiating properties are often determined by analyzing how the substance responds to energy exchanges of different types (e.g., mechanical, thermal, electrical, electromagnetic) or to interactions with other substances.

**II. Structure Determination.** Experimental evidence strongly suggests that a macroscopic sample of any given substance can be modeled as a large dynamic ensemble of identical submicroscopic units. Chemical substances differ in the composition and structure of such molecular entities.[30] The detection, identification, and quantitation of chemical substances is greatly simplified by the determination of the chemical structure of its molecular entities. This structure can be inferred from the analysis of experimental data about a substance's properties: particularly, using spectroscopic data resulting from studies involving light−matter interactions.[31] Information about chemical structure can also be derived from the analysis of patterns of interaction between different molecular entities that result in the formation of new submicroscopic units not previously present in a system (i.e., chemical reactions). The characterization of patterns of interaction between different molecular entities is important not only for determining the identity of any given substance but also in developing strategies for synthesizing new substances and controlling transformations.

### Bridging Ideas for Practice

Chemical scientists operate in the macroscopic world of chemical substances and in the submicroscopic world of molecular entities. The effective transition between these two levels of analysis is based on a set of central ideas for practice that serve as bridges between them. One of these ideas helps build relationships between the composition and structure of molecular entities and the physical and chemical properties of chemical substances (Property Prediction). A second idea for practice (Reaction Analysis) directs our attention to the major drivers and constraints for chemical transformation acting at the submicroscopic level. Finally, the third bridging idea for practice (Reaction Control) highlights the strategies commonly used to control chemical processes.

**III. Property Prediction.** The measurable physical and chemical properties of a substance are determined by the composition and structure of its molecular entities.[32] Analysis of the chemical structure of molecular entities can be used to make predictions about how they will interact with similar or different particles, and about the outcome of such interactions. In particular, the presence of specific structural patterns (e.g., functional groups) provides cues for predicting physical and chemical behaviors at the macroscopic and submicroscopic levels, including the likelihood of a transformation, the nature of the products of a chemical reaction, and the path followed by molecular entities as they transform from reactants into products (reaction mechanisms).

**IV. Reaction Analysis.** Understanding the drivers of chemical processes and the constraints affecting such transformations is critical for reaction design and control.[33] The extent of a chemical reaction is related to the relative potential energy of the molecular entities that comprise reactants and products, and to the number of different configurations that such molecular entities can adopt. Differences in these submicroscopic properties manifest as differences in measurable free energies that can thus be used to predict reaction extent. On the other hand, the rate at which a chemical process occurs is determined by the mechanism that leads to the transformation of reactants into products. This transformation often takes place in a sequence of dynamic steps that occur at a speed that depends on the fraction of interacting molecular entities that reach a state that can evolve into new products. Understanding how the nature and energy cost for the formation of these “activated states” relate to the composition and structure of interacting particles is key to explaining, predicting, and controlling reaction rates.

**V. Reaction Control.** The extent and rate of chemical reactions depend on the composition and structure of the molecular entities of reactants and products, and on the conditions in which their interactions take place. Understanding how environmental conditions affect the energy states of the different molecular entities present in a chemical system and their access to different configurations facilitates reaction control. This control may be achieved by, for example, selecting reactants based on the structure of their molecular entities, varying the concentration of reactants and products, changing temperature and pressure, choosing different solvents, or adding other chemical species that may facilitate or hinder interactions between relevant molecular entities.

### Contextual Ideas for Practice

The work of chemical scientists influences and is influenced by the context in which it takes place. The production and consumption of chemical products have benefits, costs, and risks in various dimensions, including the social, economical, political, environmental, ecological, and ethical spheres.[14] Consequently, one should expect the chemical enterprise to be guided by the following central idea:

**VI. Sustainable Action.** Chemical activities rely on diverse natural resources in the production of substances and the development of processes that can have many social, economical, political, environmental, ecological, and ethical consequences. Chemical products and processes should thus be designed to reduce consumption of material and energetic resources, produce less waste, generate fewer hazardous materials, and use renewable resources whenever possible.[34] The development, distribution, and consumption of chemical products entail costs and risks that need to be identified, evaluated, publicly discussed, and clearly communicated to all stakeholders.[35] Chemical activities should have the interests of the public, the improvement of the human condition, and the respect for environmental quality as primary goals.

## ■ FINAL COMMENTS

The proposed framework for the central ideas of chemistry (Figure 1) seeks to make more explicit the relationship between core understandings in the discipline and the practices that they enable and the aims to which they serve. It also highlights how these central ideas for practice relate to one another and work at different levels to help us make sense of the properties and changes of matter, and act on the material world to analyze it and transform it. The ideas described in this commentary encapsulate the fundamental knowledge included in Table 1, but using a practice-centered frame that more authentically reflects the nature of chemistry.

Chemical knowledge is vast and complex. It includes diverse theories, laws, and models about the properties of chemical substances and associated molecular entities, as well as large amounts of analytical and chemical reactivity data. From an educational perspective, the central ideas of chemistry help reduce such complexity by acting as lenses that uncover core understandings to guide the development of curricula, learning objectives, and assessments. Consequently, how central ideas are framed affects what is taught and evaluated. If central ideas are presented as descriptive statements of fundamental knowledge, without much reference to the types of questions and problems they allow us to confront, it is likely that instruction and assessment will focus on the mere acquisition of such knowledge rather than on the development of understanding through application in authentic contexts.

Translating the central ideas highlighted in this commentary into fruitful curricula and instructional practice demands a shift in the way we engage students with core chemistry content. Traditional chemistry curricula are structured as sequences of topics to be covered from week to week, guided by content-oriented questions: What types of substances exist? What is the structure of atoms? How do we calculate energies of reaction? This approach does not help students learn how to use chemical thinking to answer questions that are relevant to them, their future professions, or the societies in which they live.[36] Imagine, in contrast, a curriculum in which the questions that guide class conversations target core disciplinary aims:

How do we identify substances? How do we predict their properties? How do we control chemical reactions? The search for answers to these questions may be orchestrated in different contexts: Analyzing pollutants in the environment, designing polymeric materials, controlling drug degradation. The adoption of this approach in general chemistry courses in my institution has led to improved student achievement and increased motivation.[15]

Transforming an entire curriculum is a daunting task. However, instructors can begin the reform process by changing the nature of the questions, activities, and assessments that they use in their classes. Traditional classroom tasks often demand that students demonstrate acquisition of factual knowledge or application of basic skills. Activities that are more aligned with the framework advanced in this commentary should engage students in making decisions that replicate as much as possible the kinds of judgments frequently made by chemical thinkers.[37] These tasks should make real and visible the significance of targeted concepts.[38,39] For example, given a phase diagram for $CO_2$, a traditional question may ask students to infer the normal sublimation point of the substance. A more authentic task using the same information could engage students in designing strategies to extract $CO_2$ from the surrounding air.

There are certainly different ways in which the central ideas of chemistry may be framed. The proposed framework is guided by the belief that we need to better align chemistry education with the actual goals, practices, ways of thinking, and implications of the discipline.[18,40−42] This alignment would help us make the chemistry taught in schools and colleges more useful, relevant, and intellectually stimulating for students and more productive to the professions these individuals may join and to the societies in which they will live. We need to reformulate core understandings to make their purpose and implications more explicit. We need to merge content and practice to engage students in more authentic chemical thinking. And, we need to narrow down our learning targets while multiplying the opportunities to apply them in diverse relevant contexts.

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### Notes

The authors declare no competing financial interest.

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