Why and How to Foster Chemical Thinking?

Historically, the teaching of chemistry has been organized in a topical manner based on the concepts and ideas we would like our students to understand. For example, we want our students to understand the atomic and molecular structure of matter, or to learn stoichiometry, or to become familiar with acid-base reactions. When we plan our lessons, we then typically ask ourselves what it is that we want our students to *know* and how to best help them acquire such knowledge.

Imagine that, instead of guiding our planning and instruction in terms of what we want students to know, we focused our efforts on first identifying the questions we want them to learn *how* to answer. What are essential and relevant questions that our existing chemical knowledge, specialized ways of thinking, and experimental methodologies help us to answer? Although different people may have different opinions, we claim that chemistry is a powerful way of knowing, thinking, and acting that helps people in a variety of disciplines, from biology to engineering, from art to sports, to provide answers to the following six essential questions in different contexts:

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)

What are the consequences of those changes?
(the question of Benefits-Costs-Risks)

The essential questions listed in the previous page take different forms in diverse contexts. For example, under the essential question "*What is this material made of*? (the question of identity)" we can place questions of importance in medicine such as: "What toxic material was ingested? What is the concentration of cholesterol or oxygen in the blood?" In environmental sciences, questions might take forms of: "What pollutant is accumulating in the water? What levels of ozone are present in the air we breathe?" In engineering, relevant questions might be: "How does the composition of these construction materials differ? What substances need to be eliminated by this filtering device?" Or in art, we might ask: "What substance generates the color in this pigment? What material can be used to restore this paint?"

Although the specific answers to all these different questions will differ from one situation to another, there are common chemistry ideas, disciplinary practices, and ways of thinking that facilitate finding those responses. For example, the answers to the *chemical identity* questions listed in the previous paragraph require identifying at least one unique differentiating property of the materials we want to identify, isolate, or quantify, and one experimental strategy that allows us to measure or take advantage of that property for the desired purposes. If this is the case, shouldn't one our major goals in chemistry education be to help students recognize what properties and techniques are most commonly used to address these types of problems by actively engaging students in thinking about and acting on these questions in realistic contexts?

When we advocate for focusing chemistry instruction on developing chemical thinking, what we are proposing is to direct our educational efforts to help students develop the core chemistry understandings, practices, and ways of reasoning that enable professionals in different fields to find answers to relevant and critical questions in our world. We are proposing to use questions of relevance to actively engage students in developing and applying ways of thinking that they can transfer to other contexts. Although most of our students will not become professional chemists, they will continue to use chemical ways of knowing, thinking, and acting throughout their lives to form and answer questions of relevance to them. To make this possible, we encourage teachers to open diverse opportunities for students to actively engage in the search for answers to meaningful questions, make students thinking visible by publicly eliciting their ideas, carefully listen and respond to students' ideas to guide their thinking, and press all learners to think deeply and expand their understandings.

When using a *chemical thinking* approach to the teaching of chemistry one may worry about the inability to cover all the concepts that students "need to know." We need to reflect, however, on the extent to which those concepts are critical for answering questions of importance and relevance in the modern world. In fact, we are convinced that by taking a chemical thinking perspective to curriculum and instruction, teachers will be in a better position to meet the goals of the *Next Generation Science Standards* which advocate the integration of central ideas, science practices, and crosscutting ways of reasoning in the analysis of important phenomena in our surroundings. This level of integration is more easily achieved when work in the classroom is guided by essential questions whose answers demand connecting different types of understandings rather than by isolated topics that tend to focus the attention on decontextualized disciplinary knowledge.