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Humanizing Chemistry Education: From Simple Contextualization to Multifaceted Problematization

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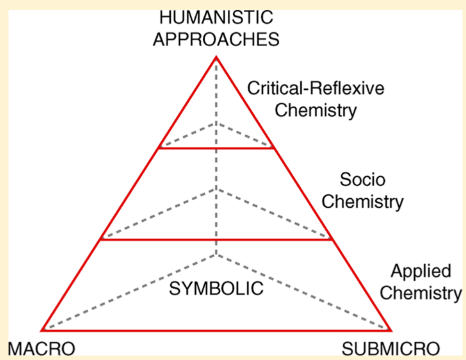
ABSTRACT: Chemistry teaching has traditionally been weakly connected to everyday life, technology, society, and history and philosophy of science. This article highlights knowledge areas and perspectives needed by the humanistic (and critical−reflexive) chemistry teacher. Different humanistic approaches in chemistry teaching, from simple contextualization to socioscientific orientations to multifaceted problematization, are discussed. The latter is crucial for "critical chemistry teaching", which includes both problematized content knowledge *in* chemistry and problematized knowledge *about* chemistry and chemistry education (about the nature of chemistry, its role in society, and the way it is communicated inside and outside the classroom). We illustrate how various facets of chemistry knowledge for teaching can be used to characterize different levels of complexity in the integration of the human element into chemistry education.



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■ INTRODUCTION

Traditional approaches to chemistry education at all grade levels tend to be content-focused, with a strong emphasis on student understanding of disciplinary concepts and ideas.[1] In general, there is too little consideration of science, technology, society, and environment (STSE) issues in which chemistry knowledge and practices play a central role. As suggested by Van Berkel and collaborators, "student activities in mainstream school chemistry [...] do not put emphasis in the curriculum on personal, socio-scientific and ethical questions that are relevant to students' lives and society" (p 33).[2]

The preparation of chemically literate citizens and responsible chemical scientists and professionals demands more than a solid understanding of fundamental chemistry principles. Driver et al.[3] defined "scientific literacy" as knowledge about (a) scientific concepts and models, (b) scientific processes, and (c) societal contexts in which science is of relevance. Chemistry education has traditionally focused on facet (a) in this list, failing to engage students in activities and discussions that foster learning about how chemistry ideas may be used to address, reflect, or make decisions about relevant personal, societal, or environmental problems.[4] Unfortunately, as expressed by Talanquer, "chemistry teachers seem to hold a monofaceted and unproblematic view of the subject matter" (p 832)[5] that limits their ability to approach the teaching of chemistry in more meaningful and relevant ways.

Hodson characterized citizen's desirable knowledge about science as "developing an understanding of the nature and methods of science, an appreciation of its history and development, and an awareness of the often complex interactions among science, technology, society and environment" (p 23).[6] In this article, we explore ideas that may help us approach chemistry education in ways that are better aligned with such an ambitious learning goal. We seek to discuss and integrate multiple ideas[5,7,8] that can support multifaceted approaches to chemistry teaching. We call such integrated approaches *humanistic chemistry teaching*, which we see as in line with humanistic perspectives in science education as discussed and described by Aikenhead.[9,10]

According to Donnelly, the humanities are characterized by a focus on human meaning (e.g., ethical values) and "an autonomous self with the right to make independent judgments and interpretations" (p 762).[11] Our contribution highlights knowledge areas and perspectives that teachers and instructors should consider while developing and implementing "humanistic" approaches to chemistry teaching. In particular, we discuss humanistic approaches that go from simple contextualization to socioscientific orientations to multifaceted problematization. We use critical-reflexive considerations to problematize chemistry content and practices within these different humanistic approaches. Additionally, we discuss how to use different

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facets of chemistry knowledge[5] to differentiate between various humanistic perspectives to chemistry education.

DIFFERENT HUMANISTIC PERSPECTIVES

Various authors have proposed different models or theoretical frameworks that seek to highlight or integrate humanistic and social components in the conceptualization of chemistry teaching.[1,12,13] For example, Mahaffy[14,15] suggested a tetrahedron model that includes Johnstone's[16,17] chemical triangle at its base (see Figure 1). This bottom triangle, also referred to as the chemistry triplet, includes the formal aspects of chemistry teaching: the *macroscopic* properties and behaviors of chemical substances, the *submicroscopic* models used to describe, explain, and predict chemical properties and phenomena, and the *symbolic* representations developed to represent chemical concepts and ideas.[16−21] In Mahaffy's model, the top of the tetrahedron represents the *human element*, including both relevant contexts and productive practices.

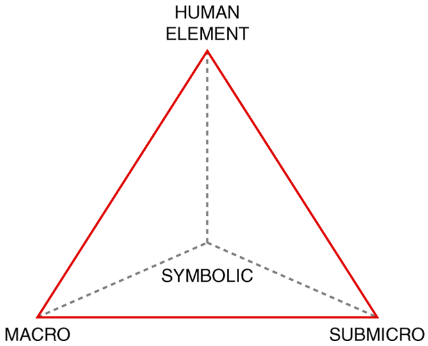

Figure 1. Mahaffy's tetrahedron,[14,15] which complements Johnstone's triangle[16,17] with an apex representing the human element in chemistry education.

Sjöström[7] has proposed that Mahaffy's tetrahedron could be enriched by recognizing different levels of complexity in the analysis of humanistic aspects in chemistry education. These levels may be represented as different layers of the tetrahedron as one moves from the disciplinary bottom triangle toward the humanistic apex (see Figure 2). The first level in this progression, identified as *Applied Chemistry*, characterizes approaches to chemistry education that introduce the human element by focusing on everyday-life issues and different applications of chemistry. At a higher level of complexity, labeled *Sociochemistry* in Figure 2, the teaching of chemistry includes approaches aimed at evaluation of the development and uses of chemistry knowledge, practices, and products, as well as understanding of the sociocultural embeddedness of scientific work and ideas. At the top of the enriched tetrahedron, "Critical-Reflexive Chemistry" engages students in a reflective analysis of historical, philosophical, sociological, and cultural perspectives, as well as in critical-democratic action for socioecojustice. In general, the bottom of the tetrahedron in Figure 2 is characterized with disciplinary and formal aspects of chemistry. The first level, *Applied Chemistry*, is characterized with pragmatic aspects of the discipline, and the top of the tetrahedron—the second and third levels—with different reflective aspects.[7,22]

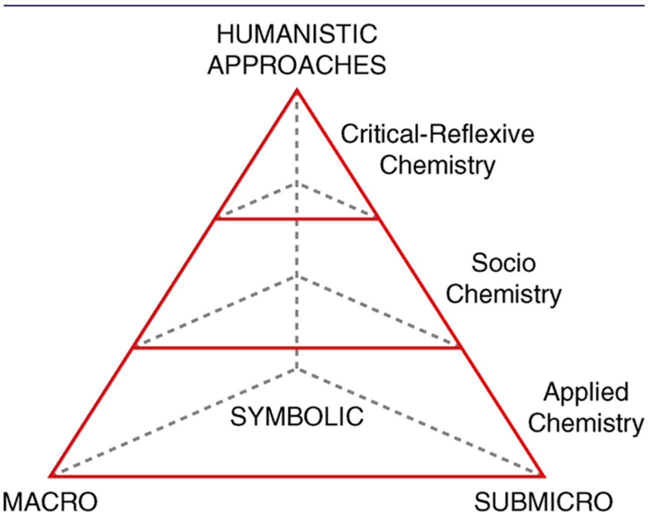

Figure 2. Sjöström's tetrahedron[7] including different levels of complexity in the analysis and discussion of the human element.

The different levels of complexity in the analysis of the human element represented in Figure 2 are related to different orientations or strands of STSE education. Recently, Pedretti and Nazir[23] proposed to arrange these various STSE perspectives in different categories, from *Application/Design*-oriented (focusing on problem solving; related to Level 1 in Figure 2) to *Historical*- and *Logical Reasoning*-oriented (focusing on (a) understanding historical embeddedness of disciplinary chemistry or (b) decision making about complex issues through consideration of empirical evidence; corresponding to Level 2 in Figure 2) to *Sociocultural*-, *Value centered*-, and *Socioecojustice*-oriented (focusing on (a) understanding how sociocultural issues influence, and have influenced, scientific ideas and practices or (b) ideologically informed decision making and action; corresponding to Level 3 in Figure 2).

Recently, Hodson has argued for four levels of sophistication of issues-based science education:[24] (i) appreciating the societal impact of scientific and technological change (related to Level 1 in Figure 2), (ii) recognizing that decisions about science and technological development are taking in pursuit of particular interests (related to our Level 2), (iii) developing one's own views and value positions, and (iv) preparing for and taking actions on socioscientific and environmental issues (the latter two are related to our Level 3).

According to Gilbert, the function of using contexts in chemical education is that students "...be able to provide meaning to the learning of chemistry; they should experience their learning as relevant to some aspect of their lives and be able to construct coherent 'mental maps' of the subject" (p 960).[25] Gilbert described four models of context and claims that there may be a steady progression from Model 1 to Model 4. In Model 1, which best corresponds to Level 1 in Figure 2, applications are solely used to illustrate the significance of disciplinary concepts. In Model 2, contexts are not conceived as static constructs to which chemical knowledge is applied, but rather they actively affect the meaning attributed to the concepts. Model 3 is characterized by the active involvement of the learner in giving meaning to the content in relevant contexts. Models 2 and 3 can be placed at the Sociochemistry level in Figure 2. Finally, in Model 4, the social dimension of context becomes essential as students actively engage in critical reflection (Level 3 in Figure 2).

In a different approach, Talanquer[5] described ten complementary facets of chemistry knowledge for teaching. These facets are referred to as (1) Essential Questions, (2) Big Ideas,

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(3) Crosscutting Concepts, (4) Conceptual Dimensions, (5) Knowledge Types, (6) Dimensional Scales, (7) Modes of Reasoning, (8) Contextual Issues, (9) Historical Views, and (10) Philosophical Considerations. At a first glance, the first seven facets in this list may be seen as aspects of chemistry teaching residing on the disciplinary bottom of Figures 1 and 2 (i.e., the chemistry triplet). They seem to refer to different aspects of the subject matter we want students to learn (e.g., central disciplinary ideas). Only the last three facets in Talanquer's list seem to explicitly address humanistic issues. Nevertheless, as we will illustrate below, all of the facets may be used to characterize different levels of complexity in humanistic approaches to chemistry education.

DIFFERENT LEVELS OF COMPLEXITY

The different levels of complexity in the analysis of the human element in Sjöström's tetrahedron (see Figure 2) can be characterized by paying attention to different facets of chemistry knowledge for teaching as described in the following paragraphs.

Level 0—Pure Chemistry

The triangular base of the tetrahedron in Figure 2 encapsulates approaches to teaching and learning of chemistry that are mostly focused on the development of fundamental disciplinary knowledge. According to Eilks et al., most traditional chemical teaching programs belong to this level as they "do not include technical applications of chemistry, societal issues, or personal related ideas" (p 20).[1] As indicated by Aikenhead,[9] science teachers tend to favor abstract "pure science", and thus, it is not surprising that decontextualized chemistry courses are still predominant in many countries around the world. At this low level of complexity in the humanistic dimension, contextual, philosophical, and historical facets of chemistry knowledge and practices are not considered, and the essential questions (e.g., how chemical bonds form?), big ideas (e.g., matter is atomic), and crosscutting concepts (e.g., chemical bonding) guiding chemistry curricula are centered on the learning of core theoretical concepts and basic experimental techniques.

In general, existing approaches at the *Pure Chemistry* level tend to emphasize the manipulation of symbols and formulas (i.e., emphasis on "visualizations" for the facet of knowledge types[5]), with a focus on compositional and structural aspects of chemical systems (conceptual dimension), which are mostly described and analyzed at the molecular level (dimensional scale). The wide scope of these types of programs often leads students to rely on rule-based and case-based reasoning (modes of reasoning) when confronting chemistry questions and problems. However, these shortcomings are not inherent to the *Pure Chemistry* approach and several educational initiatives have been directed at improving chemistry education within this perspective. Many of these reform efforts emphasize the need to engage students in model-based reasoning,[26] helping them build and connect explanations at multiple levels of representation.[19]

Level 1—Applied Chemistry

A common approach to bringing everyday-life and societal aspects into chemistry teaching relies on the use of examples of application to illustrate relevance. These examples may be introduced in an isolated manner or serve as a guide in organizing the presentation of fundamental chemistry content. However, at this level, chemical ideas, practices, and products are not problematized and tend to be presented, using Vesterinen et al.'s words, "as almost exclusively beneficial for human beings" (p 208).[27] Stuckey et al. indicate that "still [...] today in some context-based science curricula, [...] the contexts of science teaching [...] remain largely detached from their social, ecological, and economical implications" (p 5).[28] The role of chemistry in society is then illustrated at an instrumental level and everyday-life connections are made within what Aikenhead[9] calls trivial everyday contexts. The philosophical facet is commonly absent, and any historical perspectives that may be present are likely in the form of historical anecdotes, with little discussion and analysis of the central questions and concerns that drove the development of chemical ideas and practices.[8] For example, in a recent study of Nordic chemistry textbooks, Vesterinen et al. showed that historical examples were mostly anecdotal and that "the practice of chemistry is portrayed as a highly systematic, asocial, uncreative, and masculine activity that evolved within Euro-American culture" (p 1850).[29] Furthermore, it is common for important environmental aspects to be excluded from educational resources, as shown by Christensson and Sjöström in a recent study of thematic chemistry videos available online.[22] To some extent, existing curricula in the Chemistry-in-Context tradition are often built at this level of complexity in the humanistic dimension.[30,31]

At this *Applied Chemistry* level, essential questions guiding instruction may refer to relevant social and environmental issues (e.g., how greenhouse gases work?) and big ideas may be more contextualized (e.g., many energy sources commonly used by humans are forms of chemical energy). Crosscutting concepts can include overarching themes of importance to modern societies (e.g., human health). Nevertheless, the underlying chemistry concepts, ideas, and practices remain unproblematized and are often addressed in a partial and unreflective manner. For example, in a thematic chemistry video about energy and climate analyzed by Christensson and Sjöström,[22] no mention is made about problems related to energy requirements of modern societies. Although the current search for new energy sources is discussed, no analysis is presented of how net emissions of carbon dioxide from fossil fuel consumption contribute to the enhanced greenhouse effect.

In general, the introduction of applications at the *Applied Chemistry* level tends to focus instruction on the analysis and discussion of actual "experiences" in the real world, which often decreases the emphasis on the mere interpretation and manipulation of chemical visualizations of the systems of interests (knowledge types), and helps teachers and students build connections between macroscopic and submicroscopic (mesoscopic, multiparticle, supramolecular) levels of representation (dimensional scales). Furthermore, the focus on relevant contexts of application often brings the energy dimension to the forefront, improving the balance between energy and composition/structure considerations (conceptual dimensions). Unfortunately, a larger focus on relevant applications of chemistry knowledge and practices does not necessarily translate into an increased emphasis on model-based reasoning over rule-based or case-based reasoning (modes of reasoning).

Level 2—Sociochemistry

At this higher level of complexity in the humanistic dimension, one can identify two major educational approaches that seek to integrate the human element in different ways: (a) sociohistorical, which is oriented toward the epistemological and, to some extent, sociological analysis of the development of chemical knowledge and (b) socioscientific, which emphasizes science-based decision-making about issues at the interface between science, technology, society, and environment.

Within the sociohistorical strand, disciplinary chemistry is seen as a human endeavor and efforts are directed at understanding the historical development of chemistry knowledge. As Eilks et al. state, "chemistry curricula oriented on the history of science (HOS) try to make explicit that chemical facts and theories have a genesis [...] Learning about the historical genesis of fundamental theories of chemistry can help students learning about the nature of chemistry" (p 21).[1] Chemistry ideas and practices are seen as cultural products developed by chemists working in particular contexts and subject to change in the light of new evidence. The use of this historical approach to chemical education has been discussed by Wandersee and Griffard.[32] In particular, these authors describe an instructional technique called Interactive Historical Vignettes in which a nature-of-science incident in the life and work of one or several chosen chemists is dramatized. In a recent analysis of lesson plans where a historical approach is used to teach the nature of science (NOS), Tolvanen et al. concluded that to "increase the coherence and clarity of learning objectives and instruction, each lesson plan should focus on the limited amount of specific NOS issues instead of several overtly general NOS aspects".[33]

The other strand in *Sociochemistry*, labeled as socioscientific, emphasizes science-based decision-making concerning chemistry applications in modern societies. As described by Eilks et al., "socio-scientific issues, e.g. the use of bio-fuels, are not only dealt with concerning their scientific and technological background, but also ethical and societal values of their use and consequences to society are reflected" (p 5).[1] Practices and products of chemistry in society are highlighted, and their benefits, costs, and risks are emphasized. Many of the educational initiatives within this strand can be seen as examples of Education for Sustainable Development (ESD) as discussed by Burmeister et al. in a recent perspective paper;[34] they are driven by democracy and sustainability issues,[7,35−37] and are concerned with benefit−cost−risks relations. Examples of the application of this perspective, thus, include analyses and discussions of the social, economical, and environmental costs and benefits of chemical activities and their products. For example life-cycle analysis (LCA) has recently been shown to be of potential use in ESD-driven chemistry education.[38]

At the socioscientific level, essential questions guiding instruction refer to relevant societal and environmental issues (e.g., How can we evaluate the quality of the water we drink?). Big ideas guiding the curriculum link disciplinary knowledge and practices to their costs and benefits for modern societies. For example, students should be expected to realize that the "capacity of chemistry to change the material world has had significant consequences, both positive and negative, on the relationship between chemistry and society" (p 85).[39] Crosscutting concepts are selected from a socioscientific point of view, looking to focus the introduction and discussion of chemical knowledge on the analysis of its personal and social relevance. One of such crosscutting concepts could be *sustainable development*. Vilches and Gil-Pérez[37] have stated that sustainability issues are practically absent from high school and university chemistry curricula across the world. They thus argue for chemistry education that focuses on the search for possible solutions for a sustainable future.

A socioscientific educational approach is expected to be proactive, focusing not only on building models to explain chemical phenomena but also on discussing how to use chemical models and ideas to prevent problems and find solutions. Students are expected to integrate different knowledge types (experiences, models, visualizations) at various scales (from macro to submicro), as they engage in practical activity to address relevant issues. As learners give meaning to the content while solving authentic problems, they are asked to consider various conceptual dimensions of analysis, from composition/structure to energy to time issues. Concrete examples of this integrative and contextualized perspective have been developed and discussed by Marks and Eilks[40] and by Bulte and collaborators.[41,42] These latter authors have designed a variety of contextualized educational units built around structure−property relationships as a crosscutting concept. Recent educational efforts in the area of green chemistry also fall within this humanistic level.[43,44] In this case, the work focuses on producing, using, and disposing of chemicals in order to reduce their environmental impact.

Level 3—Critical-Reflexive Chemistry

Due to the technoscientific nature of chemistry,[8] the teaching of our discipline creates rich opportunities for analyzing, discussing, and reflecting on the complex interactions between chemistry, technology, society, and environment, from integrated sociological, historical, and philosophical points of view.[7] The top level in the tetrahedron in Figure 2, thus, includes *sociocritical* reflection about the role of chemistry in society, as well as *critical-philosophical* reflection about chemistry knowledge production and application. Both content knowledge *in* chemistry and knowledge *about* chemistry and chemistry education (about the nature of chemistry, its role in society, and the way it is communicated inside and outside the classroom) are thus problematized. *Critical chemistry teaching* emphasizes uncertainties in knowledge generation and application, and engages students in critical reflection about the nature of chemistry and of chemistry knowledge. A critical chemistry teacher enables students "to express, in a personal voice, judgments, interpretations, and arguments which are 'free yet disciplined'" (p 768).[11] At this highest level of complexity in the humanistic dimension, one can identify two major educational approaches: (a) sociocultural-philosophical, which is oriented toward understanding and problematizing scientific ideas and practices (including classroom practices) and (b) sociopolitical-ethical, which emphasizes ideologically informed decision making and action about issues at the interface between science, technology, society, and environment. Similarly, Tan and Calabrese Barton[45] (reviewed by Ebenezer[46]) have constructed a conceptual web with three "criticalities": *critical consciousness* (corresponding to our Level 3a), *critical literacy* (corresponding to both Level 3a and 3b), and *critical agency* (corresponding to Level 3b).

In a *Critical-Reflexive Chemistry* perspective, chemistry knowledge and practices are not only applied to make decisions and solve problems in relevant contexts. The nature and culture of such knowledge, and of the knowledge-production practices, is also critically analyzed. The essential questions that are addressed include concerns such as: What social, economical, and political factors influence the generation of chemical knowledge? What criteria have been used to accept or reject new chemical models or ideas in different historical periods and sociological contexts? What implicit assumptions about the

Table 1. Ten Facets of Chemistry Knowledge As Manifested in Common Educational Approaches Working at Different Levels in the Humanistic Dimension

Facets of Chemistry Knowledge	Level 0 – Pure Chemistry	Level 1- Applied Chemistry	Level 2- Socio Chemistry		Level 3- Critical-Reflexive Chemistry	
			a) Socio-historical	b) Socio-scientific	a) Socio-cultural	b) Socio-political
Essential Questions	Focus on core disciplinary queries: *What types of matter are there?*	Focus on questions of public interest: *How can we design new drugs?*	Focus on questions about the nature of knowledge: *How have ideas about atomic structure evolved?*	Focus on questions of relevance to individuals and modern societies: *Which type of fat should we eat?*	Include questions about knowledge development and application: *What factors influence the choice of fossil fuels over other sources?*	Include value-centered questions of relevance to a sustainable society: *Should perfluorinated chemicals be allowed on Earth?*
Big Ideas	Include fundamental ideas in the discipline: *Matter is atomic*	Include ideas of relevance in modern times: *Combustion engines produce greenhouse gases*	See Level 0	Include ideas that integrate STSE issues: *Green chemistry seeks to use less energy and produce less waste*	Include ideas of understanding and problematizing science and technology systems in socio-cultural context: *Between the public and the scientific communities there are often differences in values, perspectives on problems, and preferred solutions*	Include ideas that problematize STSE issues aiming at transformation for critical citizenship and socio-ecojustise: *The chemical industry has generated more benefits and fears than any other sector*
Crosscutting Concepts	Refer to central disciplinary concepts: *Chemical bonding*	Refer to current societal concerns: *Pollution*	See Level 0	Refer to central STSE issues: *Sustainable development*	Refer to and problematizes central STSE issues: *Sustainability*	See Level 3a
Conceptual Dimensions	Commonly focused on the *composition/structure* dimension	Tend to focus on *composition/structure* and *energy* dimensions	See Level 0	Seek to integrate *composition/structure*, *energy*, and *time* dimensions	See Level 2b	See Level 2b
Knowledge Types	Frequently emphasizing interpretation and manipulation of *visualizations* (symbolic representations)	Emphasis on connecting *experiences* and *models* using appropriate *visualizations*	See Level 1	See Level 1	See Level 1	See Level 1
Dimensional Scales	Commonly focused on *submicroscopic* descriptions	Focused on building connections between *macroscopic* and *submicroscopic* descriptions	See Level 1	Focused on building connections between descriptions at various dimensional scales	See Level 2b	See Level 2b
Modes of Reasoning	Frequently emphasizing *rule-based* and *case-based* reasoning	Emphasis on *case-based* and *model-based* reasoning	Emphasis on modes of reasoning appropriate for particular goals and contexts	See Level 2a	See Level 2a	See Level 2a
Contextual Issues	If addressed, only as isolated scenarios for numerical problems	Addressed in an isolated manner or to serve as a guide in organizing the presentation of fundamental chemistry content	Socio-cultural embeddedness of scientific ideas and individual scientists´ work	Contextual issues used to organize the curriculum	Socio-cultural embeddedness of science and technology	Critical-democratic issues used to engage students in decision making and practical activity in both local and global contexts
Historical Views	Not addressed	Marginally addressed as anecdotes and isolated vignettes	Consideration of historical developments of relevance to the issues at hand	See Level 2a	Consideration of historical contexts	Consideration of historical contexts in judgment and decision-making
Philosophical Considerations	Not addressed	Not addressed	Nature of knowledge aspects are considered, including problematization of chemical concepts, laws and models	Recognition of ethical and moral dilemmas	Philosophical considerations about the nature of chemistry knowledge are taken into account	Philosophical considerations include integration of ethical and moral concerns in judgment, decision-making and actions

nature of the world are behind the chemical models and practices that guide current investigations about systems of interest? Associated big ideas should consider social, historical, and philosophical issues, such as the dual nature of chemistry which can be conceived as both science and technology, mixing intellectual pursuits with practical concerns.[47] From this perspective, the idea of *technoscience* could be used as a crosscutting concept to guide the critical analysis of the nature of chemical knowledge and its social, economical, and political roles across history.[48]

Critical-Reflexive Chemistry demands additional problematization of chemical ideas, models, and practices from a philosophical point of view. It requires analysis and discussion of, for example, which chemical ideas should be taken as central and why, how the selection and use of chemical models depends on the goals and context of application,[49] and what practices are central to the chemical enterprise.[8,50] This approach invites us to critically analyze the different ways of knowing and generating arguments and explanations in the discipline (e.g., case-based or model-based reasoning), weighing their pros and cons.[51] It also leads us to critically reflect on how knowledge is represented and communicated, considering different dimensional scales and conceptual dimensions.[8] One could argue that content analyses such as that of Johnstone,[16,17] which made explicit different levels of representation used in the discipline, historical analyses such as that of Jensen,[52] which integrated dimensional scales and conceptual dimensions of chemistry knowledge, pedagogical reflections such as that of Talanquer[20] or Taber,[21] which problematized the interpretation of the chemistry triplet, and pedagogical models such as that of Sevian and Talanquer,[50] which highlighted critical aspects of chemical thinking, are intellectual exercises that support the implementation of *Critical-Reflexive Chemistry* perspectives.

At the *Critical-Reflexive Chemistry* level "the larger cultural milieu in which scientific discoveries and innovations were made" (p 1850)[29] is considered. Science and chemistry history, together with contemporary chemical research practice, are approached in multifaceted ways, bringing to the forefront the central questions that drove the development of chemical ideas and practices and critically analyzing traditional historical accounts of the development of chemical knowledge. Two case studies that illustrate the application of these types of perspectives have recently been published in this journal. The first of these cases analyzes the work of Thomas Midgley in the development of tetraethyl lead as an antiknock gasoline additive and of chlorofluorocarbons (CFCs) as fluids for refrigeration devices.[53] As stated by the authors of this case study, its general aim "is to display the complex nature of science, including the relation of science to technological and social issues, the nonlinear and noncumulative nature of its development, and the contribution of people with different backgrounds to the construction of scientific knowledge" (p 1632).[53] On the other hand, the second case analyzes the negotiation of Niels Bohr and Werner Heisenberg in Copenhagen during World War II concerning basic atomic research and its connection to the creation of the atom bomb.[54] According to the author of this study, the case allows students to "acquire a better understanding of the continuum from scientific research to technology design, and also become aware of the many and varied interrelationships of science with history and humanity" (p 219).[54] Other modern cases with rich potential for critical reflection include the debate about DDT, illustrating the dynamics of risk knowledge production,[55] and recent developments and applications in the area of nanotechnology.[56]

CONCLUDING REMARKS

We have shown how diverse educational approaches that seek to integrate the human element into chemistry education can be characterized using different facets of our chemistry knowledge[5] as lenses for analysis. Major differences between different humanistic perspectives along each of the facets are summarized in Table 1. How can chemistry teachers and instructors benefit from such analysis? At a basic level, our analysis can be used as a rubric to evaluate the extent to which the humanistic dimension is incorporated into a chemistry course, helping identify facets that could be targeted to strengthen the presence of the human element in chemistry teaching (e.g., types of essential questions or cross-cutting concepts used to organize curricula). Although we have described different humanistic perspectives as distinct levels in Figure 2, one can expect chemistry courses to exhibit mixed facets, including elements from different perspectives.

Our analysis also highlights the wide scope of the understandings *in* and *about* chemistry and chemistry education that teachers and instructors need to develop to successfully design and implement chemistry education that incorporates humanistic perspectives. As suggested by Thomas, "Developing critical thinking in learners requires learning by the teachers, not only to support the learners, but to become 'critical teachers'" (p 257).[57] These critical teachers need to reflect on the nature of chemistry knowledge and practices from sociocritical and critical-philosophical perspectives, looking to build meaningful inferences for pedagogical practice. Such reflection requires knowledge about the history, and philosophy of chemistry, as well as critical understanding of the political, ethical, and environmental contexts in which chemistry knowledge is developed and applied. It also demands pedagogical content knowledge that integrates the understanding of chemistry with the understanding of contexts.[58]

Van Berkel et al. states that "the initiation into *normal* chemistry should be largely replaced by an education in or through fluid, *critical* and creative chemistry, together with an education in or about the relations between chemistry, technology, and society" (p 47;[2] emphasis added). From this perspective, chemistry educators should aspire to move their courses up in the tetrahedron in Figure 2, opening spaces for students' empowerment and transformation by engaging in multifaceted problematization, looking to understand uncertainties in chemistry knowledge, reflecting on the benefits, costs, and risks of chemistry and its applications, and engaging in critical-democratic action for sustainability. It is, in Hodson's words, about "assisting students in building a sense of identity as thoughtful, critical and active citizens" (p 279).[24]

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Notes

The authors declare no competing financial interest.

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