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Given the diversity of materials in our surroundings, one should expect scientifically literate citizens to have a basic understanding of the core ideas and practices used to analyze chemical substances. In this article, we use the term 'chemical identity' to encapsulate the assumptions, knowledge, and practices upon which chemical analysis relies. We conceive chemical identity as a core crosscutting disciplinary concept which can bring coherence and relevance to chemistry curricula at all educational levels, primary through tertiary. Although chemical identity is not a concept explicitly addressed by traditional chemistry curricula, its understanding can be expected to evolve as students are asked to recognize different types of substances and explore their properties. The goal of this contribution is to characterize students' assumptions about factors that determine chemical identity and to map how core assumptions change with training in the discipline. Our work is based on the review and critical analysis of existing research findings on students' alternative conceptions in chemistry education, and historical and philosophical analyses of chemistry. From this perspective, our analysis contributes to the growing body of research in the area of learning progressions. In particular, it reveals areas in which our understanding of students' ideas about chemical identity is quite robust, but also highlights the existence of major knowledge gaps that should be filled in to better foster student understanding. We provide suggestions in this area and discuss implications for the teaching of chemistry.

Keywords: *Chemistry Education; Learning Progressions; Students' Conceptions*

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Introduction

Reform efforts in science education in recent years emphasize the need to focus student learning on the development, analysis, discussion, and application of central ideas in the different scientific disciplines (NRC, 2011, 2013). They also highlight the importance of using crosscutting concepts, such as scale, structure, and energy, to analyze the properties of diverse systems and to build meaningful connections among those systems. The use of crosscutting concepts to organize curricula allows teachers to focus students' attention on the search for answers to essential questions in science, introducing unifying ideas to guide student thinking.

Crosscutting concepts highlighted in educational standards tend to be cross-disciplinary constructs, relevant in different science areas. One can also identify crosscutting concepts that are discipline-specific and may help integrate concepts and ideas within a given domain. In the particular case of chemistry, we have recently identified six crosscutting disciplinary concepts that can be used to facilitate knowledge integration in the discipline (Sevian & Talanquer, 2014). These concepts include chemical identity, structure–property relationships, chemical causality, chemical mechanism, chemical control, and benefits–costs–risks. They can be used to frame chemistry education around essential questions in the discipline, such as 'how do we identify substances?' or 'how do we synthesize chemical products?' (Hoffmann, 1995). This framework is expected to foster the development of students' capacity for authentic chemical thinking, which integrates conceptual knowledge and discipline-specific practices (Sevian & Talanquer, 2014).

Conventional approaches to chemistry education typically present the discipline as a set of loosely related topics: chemical nomenclature, stoichiometry, atomic structure, etc. (Van Berkel, De Vos, Verdonk, & Pilot, 2000). Instruction in chemistry often involves helping students develop sets of isolated skills to solve academic problems (e.g. balancing chemical equations, drawing Lewis structures). This 'toolbox' approach to the teaching and learning of chemistry has had limited success in fostering meaningful understandings among diverse students (Gabel & Bunce, 1994; Kind, 2004). The use of crosscutting disciplinary concepts to organize curricula can help alleviate these problems by directing teachers' and students' attention toward fundamental ways of thinking in chemistry that cut across a variety of topics.

In order to support the development of educational approaches that help students build connections among chemistry ideas and practices, we need to better understand the challenges that students may face as they are asked to think about chemical systems using crosscutting disciplinary concepts. Thus, the main goal of this contribution is to present an analysis of students' ideas about what we characterize as one of the core crosscutting chemistry concepts: *chemical identity*. This concept encapsulates the assumptions, knowledge, and practices used by chemists to determine whether targeted chemical entities are the same or not the same (Hoffmann, 1995). Our work is based on the review and critical analysis of existing research findings of studies on students' alternative conceptions in chemistry education, and historical and philosophical analyses of chemistry. We use the results of these studies to characterize students' assumptions about factors that determine the chemical identity of materials and to map how core assumptions change with training in the discipline. From this perspective, our work contributes to the growing body of research in the area of learning progressions (Alonzo & Gotwals, 2012). In particular, our analysis reveals areas in which our understanding of students' ideas about chemical identity is quite robust, but also highlights the existence of major knowledge gaps that should be filled in to better foster student understanding. We provide suggestions in this area and discuss implications for the teaching of chemistry at different educational levels.

Chemical Identity: A Core Chemistry Concept

All scientific disciplines focus a significant part of their efforts on differentiating the types of entities that are relevant in their domain. This is particularly important in disciplines such as chemistry that rely on classification not only for organizational purposes, but also as a powerful tool for predicting properties (Schummer, 1998). The search for proper cues to differentiate the diverse and increasing number of chemical substances in our world has been one of the core goals of the chemical enterprise throughout its history (Schummer, 2002). Modern chemical thought and practice have come to rely on the fundamental assumption that each material kind has at least one measurable differentiating characteristic that makes it unique and that can be used to identify it (Enke, 2001). Understanding chemical identity and the conditions and processes in which it is lost or preserved is a core goal of chemistry with major implications for modern societies (e.g. detecting pollutants, tracking metabolites, purifying drinking water; Hoffmann, 1995). Consequently, understanding students' ideas about this crosscutting disciplinary concept should be considered of central importance in chemistry education.

The concept of chemical identity is not trivial and its meaning has changed several times in the history of our discipline (Schummer, 2002). Processes that nowadays we conceive as conserving chemical identity, such as the transformation of ice into liquid water or the vaporization of this substance, were conceptualized as leading to the formation of new entities in the Aristotelian tradition (Toulmin & Goodfield, 1962). Elementary substances such as nickel and cobalt were thought of as mixtures of several metals by mineralogists in the eighteenth century (Llana, 1985). Although chemical scientists have identified sets of properties that facilitate the identification of chemical substances, the answer to the question of which properties count as chemically essential has changed with the development of new theoretical frameworks and experimental techniques. Historically, substances were characterized by a short set of factors: method of preparation, elemental analysis, melting or boiling point, visual characteristics, solubility in various solvents, and exemplary reactivities. Only recently has chemical structure been added as a major and dominant differentiating characteristic (Schummer, 2002). The introduction of spectroscopic methods in chemical analysis has led to a radical reconceptualization of the concept of chemical identity, from a construct that depended on the characterization of the chemical composition and properties of pure macroscopic samples to a concept which now critically relies on the determination of the molecular structure of the submicroscopic components of the substance under analysis.

Given the long and complex historical evolution of the concept of chemical identity, one may suspect that many students will struggle to develop a meaningful understanding of this construct. Existing research in science education suggests that changes in students' understanding of some core scientific concepts often resemble stages in the history of the concept's development (Wandersee, 1986). Despite the complexity of the concept, at the bare minimum, it is our view that we should aspire for scientifically literate individuals to understand that the chemical identity of substances in their surroundings is determined by their submicroscopic composition and structure. We should also create opportunities for students to identify the costs and benefits of applying chemical thinking to determining and changing the identity of materials. At more advanced levels, students should be able to recognize the emergent nature of chemical identity and the diversity of approaches that can be used to characterize it.

Although chemical identity is not a concept explicitly addressed by traditional chemistry curricula, its understanding can be expected to evolve as students are asked to recognize different types of substances, explore their properties, and identify their chemical composition and structure at the submicroscopic level. Thus, analysis of students' ideas in all of these areas should provide insights into common conceptualizations of chemical identity at different educational stages. In particular, understanding the underlying assumptions that support but also constrain student reasoning about chemical identity may help us devise strategies to effectively engage students in authentic chemistry practices and ways of thinking (Sevian & Talanquer, 2014).

Constraining Assumptions

A variety of researchers have invoked the existence of cognitive constructs, many of them tacit or unconscious, that seem to support but also constrain human reasoning in different domains. For example, Vosniadou (1994) refers to them as pre-suppositions that guide the construction of individual mental models, while Chi (2008) talks about core beliefs tightly linked to the ontological categories into which people assign the relevant entities in a domain. Similarly, diSessa (1993) conceives phenomenological primitives (p-prims) as tacit pieces of knowledge that support reasoning across different contexts. In general, these cognitive constructs can be seen as *assumptions* that individuals implicitly hold about the entities and processes under analysis. Such assumptions guide our reasoning by narrowing the spectrum of potential outcomes or highlighting likely associations between different variables. These cognitive constraints often facilitate reasoning, but may hinder understanding or bias decision-making. We expect, for example, that solid objects will always move in continuous trajectories and will persist over time (Spelke & Kinzler, 2007). This assumption helps us predict the path of moving vehicles and avoid collisions. Nevertheless, thinking of electrons as small balls when learning chemistry will lead us to assume that these particles exhibit classical behaviors, hindering our ability to comprehend current models of an atom.

We have argued that uncovering the implicit assumptions that guide student reasoning in chemistry is more productive than focusing the attention on specific misconceptions, which we conceive as particular manifestations of one or more underlying assumptions in specific contexts (Talanquer, 2006, 2009). For example, it is well established that novice chemistry students tend to assign macroscopic properties to submicroscopic particles, thinking that atoms have the same color as a bulk sample of a material (Ben-Zvi, Bat-Sheva, & Silberstein, 1986) or that such atoms expand when the sample is heated (Taber, 2002). These different alternative conceptions may be seen as stemming from a single underlying assumption: 'matter is homogeneous (i.e. it has invariant properties) at all scales.' Individuals who may be judged as having different alternative conceptions, based on analysis of their explanations of a given phenomenon, may hold similar assumptions about the properties of the components of a system. Observed differences may be due to reliance on different salient cues when building explanations. For example, in ranking the feasibility of two chemical reactions in studying a different crosscutting disciplinary concept, chemical causality, many students assume that 'the more likely reaction is the one that requires less effort' (Maeyer & Talanquer, 2013). One student may select one reaction because it involves fewer reactants (reducing the effort needed to make them react), while another student may choose the other reaction because it produces a single product (reducing the effort needed to put it together).

Underlying assumptions about entities or processes support people's development and application of dynamic mental models of systems of interest (Brown & Hammer, 2008). The nature of such assumptions can be expected to change with learning (Duit & Treagust, 2003). For example, some of these cognitive constraints may gain higher status as individuals become dissatisfied with some ideas or ways of thinking (Hewson & Lemberger, 2000). Ontological reclassification of relevant entities in a domain will likely trigger different assumptions about their properties and behaviors (Chi, 2008). In general, experiences and instruction will lead to the dynamic reorganization of the complex knowledge system of individuals (Carey, 2009; Vosniadou, 1994). Within this framework, tracking progress in understanding is thus facilitated by mapping the landscape of assumptions that most commonly guide student reasoning in a targeted area (Sevian & Talanquer, 2014). These common assumptions are not thought of as developmentally or educationally inevitable, nor as stages through which students necessarily must pass before proceeding to the next one, but are likely to influence the reasoning of a significant number of students exposed to the natural world and to conventional science curricula.

Research Question and Goals

This study was guided by the following research question:

- What major assumptions about chemical identity seem to guide students' reasoning about chemical substances as they progress from less to more conceptual sophistication?

Our specific goal was to characterize the common evolution of students' ideas about chemical identity as inferred from the analysis of existing research findings in the areas of students' alternative conceptions in science education. We seek to build a knowledge base that can aid and support the construction of a learning progression on chemical thinking. We define chemical thinking as the development and application of chemical knowledge and practices with the intent of analyzing, synthesizing, and transforming matter for practical purposes (Sevian & Talanquer, 2014). Learning progressions are educational models that describe pathways of students' expertise development in given domains (Duschl, Maeng, & Sezen, 2011). Such learning progressions can guide curriculum development as well as instructional and assessment practices to foment more meaningful learning, clearer standards of learning progress, and more useful formative feedback (Alonzo & Gotwals, 2012). The development of these educational models demands a solid understanding of students' ideas and their likely changes with instructional interventions.

Methodology

Our study was based on the review and analysis of existing findings in science and chemistry education. In particular, we analyzed the existing research literature looking to identify study participants' underlying assumptions about the answers to two major questions related to the concept of chemical identity (Sevian & Talanquer, 2014):

- What types of matter are there?
- What cues are used to differentiate matter types?

Research findings were carefully analyzed to infer assumptions about chemical identity that may have guided student thinking in the identified studies. Core inferences were often informed by our own chemistry knowledge, and by studies on the history and philosophy of chemistry that refer to the concept of chemical identity. Our analytical work consisted of several phases.

Phase 1: Initial resource collection – A list of search terms and concepts believed to be relevant to chemical identity was compiled (e.g. chemical substance, properties). The resulting list of terms was then applied to complete thorough searches using three major online databases: Web of Science, SciFinder, and Google Scholar. Initial evaluation of search results was based on the analysis of work titles and abstracts, focusing on those manuscripts that reported results on students' abilities to identify or differentiate among various chemical substances (either as a main part of the study or as one of its components). There were no restrictions on publication date for the resources collected, type of research methodology employed, country of origin, or age of the research subjects. Thus, the identified studies involved diverse participants from a wide span of educational levels and regions of the world, from pre-school to graduate levels. This initial stage of our analysis resulted in a collection of 170 works, which included articles published in journals, book chapters, online white papers, conference abstracts and papers, and doctoral theses.

Phase 2: Resource evaluation – The initial collection of resources was divided into two major categories after careful analysis of different study abstracts. The first group, or primary collection, included research on students' approaches to the classification of objects and materials, learners' beliefs about changes in chemical identity during physical or chemical changes, alternative conceptions about different types of matter, etc. The second collection included manuscripts not written in English, lacking a detailed description of findings, or indirectly related to the concept of chemical identity, such as studies focused on the analysis of students' general ideas about different models of matter. Some of these resources were moved to the primary collection during Phase 3 of our analysis.

Phase 3: Additional references – Careful reading of all of the resources in the primary collection allowed us to identify additional cited papers relevant to our investigation, which were included in either our primary or secondary collections.

Phase 4: Analysis and synthesis – Findings from each research paper in our primary collection were summarized and analyzed to elucidate student thinking. We paid particular attention to patterns of reasoning consistently elicited by several studies. Initial hypotheses about underlying assumptions guiding student reasoning were made by the first author of this article, and then discussed until consensus was reached among different authors. For those studies involving instructional interventions, efforts were made to identify both initial assumptions (held by students prior to the intervention) and targeted assumptions (seen as the desirable outcome of the intervention). The results of these analyses were used to build hypotheses about a potential evolution in student assumptions about core aspects of chemical identity. These hypotheses were also informed by both our own disciplinary knowledge and our teaching experience.

Existing data allowed us to develop a rather complete picture of the lower anchor for a learning progression on chemical identity. The lower anchor in a learning progression describes the initial ideas that many novice learners hold about a targeted concept before instruction (Duschl et al., 2011). The characterization of how these initial ideas evolve with training in the discipline was less complete, as we found major gaps in the analysis of students' ideas about substances at different educational levels. Data analysis led us to identify various ways of thinking about chemical identity that could correspond to different degrees of conceptual sophistication. We labeled such patterns of thinking (e.g. objectivization, principlism, compositionism), and their underlying assumptions (e.g. historicality, additivity, substantialism), using words that sought to capture the essence of student thinking and that had been used by prior authors in science education or in the history and philosophy of science to represent specific forms of reasoning. As part of our analysis, we also tried to identify reconceptualizations in the learning progression (Wiser, Frazier, & Fox, 2013), which are similar to threshold concepts (Meyer & Land, 2006), representing productive ways of thinking that may support the transition to more sophisticated thinking with proper instruction.

Although our literature review was thorough, there may be relevant studies that we missed in our analysis. Nevertheless, the strong consistency in core findings across the different studies included in our review substantiates the major claims made in the following section. Given space constraints, we do not cite every study that was analyzed, but only a selected set of manuscripts that highlight major trends or summarize core findings from several studies.

Findings

Our analysis of existing research findings revealed that students' ideas about chemical identity do progress with training in the discipline, but the development of canonical understandings is not straightforward. Figure 1 summarizes the major assumptions that emerged from our analysis that seem to guide the reasoning of a significant

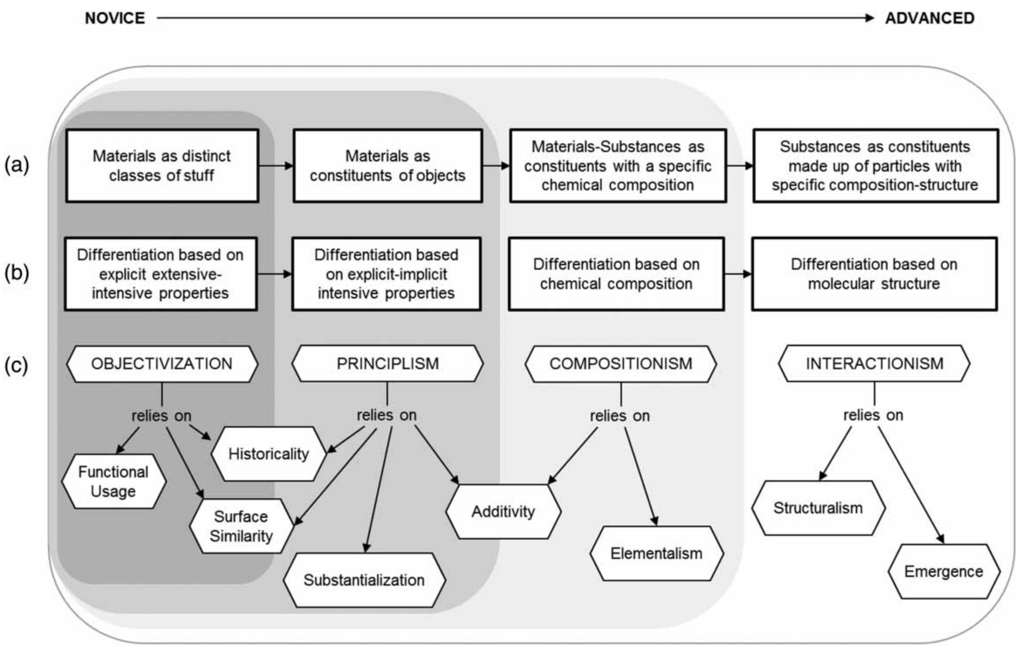

Figure 1. Hypothetical progression of major assumptions about chemical identity: (a) conceptualization of matter types, (b) types of properties used in making decisions about chemical identity, and (c) major reasoning patterns applied in making such judgments. We highlight four major ways of thinking that influence students' reasoning about chemical identity at different degrees of conceptual sophistication: 1. Objectivization: The tendency to use object-relevant properties to differentiate materials; 2. Principlism: The tendency to explain the properties of matter by reference to the presence (or absence) of 'principles' that carry such properties; 3. Compositionism: The tendency to think of substances as mixtures of atoms-elements with characteristic properties; 4. Interactionism: The tendency to view the properties of matter as emerging from the dynamic interactions among components

proportion of students at different degrees of conceptual sophistication. Assumptions are arranged into three major threads related to (from top to bottom): (a) how students conceptualize matter types, (b) what types of properties learners use in making decisions about chemical identity, and (c) what major reasoning patterns apply in making such judgments. In the following sections we describe existing evidence supporting the progression of assumptions represented in the figure.

Novice Learners (Lower Anchor)

Although humans interact with a wide variety of materials from very young age, existing research studies indicate that young children struggle to differentiate between the concepts of object and material, using object-relevant properties (e.g. size, shape) to classify different kinds of substances (Au, 1994; Dickinson, 1987; Johnson, 2000; Krnel, Watson, & Glažar, 1998, 2005; Smith, Carey, & Wiser, 1985; Vogelezang, 1987; Wiser & Smith, 2008). In reality, very few materials that learners meet in everyday life are single substances, i.e. most are mixtures. Novice learners typically do not distinguish between mixtures and pure substances. Although most children in preschool or early elementary school can distinguish an object from the material from which it is made (Au, 1994; Johnson, 2000), there is evidence that many students continue to use a mixture of object-relevant and substance-relevant properties to classify materials in secondary school (Krnel, Glažar, & Watson, 2003; Krnel, Watson, & Glažar, 1998, 2005). This tendency to 'objectivize' materials (*objectivization*) seems to have a strong influence on how students begin to think and make decisions about chemical identity.

Analysis of core results from different studies suggests that novice students' reasoning about the identity of materials is influenced by three major categories of factors: (a) appearance, (b) usage, and (c) history. These types of factors are similar to those that guide people's reasoning about object identity (e.g. deciding whether a perceived object is a chair or a table), and their application in differentiating kinds of substances is indicative of major assumptions about chemical identity described in the following paragraphs.

Surface similarity. Novice learners use perceptual cues to distinguish among different types of materials. They pay attention to perceivable properties of materials such as shape, color, texture, and smell to make judgments about category membership (Liu & Lesniak, 2006; Smith et al., 1985). What cues are used in differentiating substance may vary from one context to another, and may depend on the specific types of materials under consideration. For example, the liquidity of a set of materials often leads learners to classify them as 'like water,' or containing water, independently of differences in color, taste, or smell (Solominodou & Stavridou, 2000). Differences in the granularity of two samples of the same material (e.g. a solid piece versus a powdered sample) may lead children to classify them into two different groups, despite many apparent similarities (Dickinson, 1987). Abstraction of salient features shared by several materials may result in the development of a 'prototype' used to represent a particular type of matter. For example, gases are thought of as some type of 'air;' liquid materials are often seen as some type of 'water;' shiny solids are generically classified as 'metal;' while crystalline powders are said to be like 'salt' (Krnel, Watson, & Glažar, 1998, 2005).

The central role that 'surface similarity' plays in the categorization decisions of novice learners has been described and analyzed by a variety of authors (Vosniadou & Ortony, 1989; Wiser & Smith, 2008). When dealing with natural kinds, people often tacitly assume that surface similarity is likely indicative of common inner structures or essences (Gelman, 2003). This assumption is a powerful cognitive guide given that surface similarity may be revealing of deeper structural properties. Unfortunately, this assumption acts as a cognitive roadblock when making decisions about chemical identity because perceivable commonalities are often misleading (e.g. not all crystalline white solids are sweet, or soluble in water, or edible). Surface features used to differentiate materials may vary not only when judging different entities, but also as attention shifts from one salient feature to another during the analysis of a given material (Stains & Talanquer, 2007).

Functional usage. Combinations of actions seem to help children differentiate matter types (Krnel, Watson, & Glažar, 1998). For example, solids can be held and broken, liquids can be poured and spilled, and gases can be blown. The actions with and uses of particular substances support the identification of different classes of materials. Thus, young children also create conceptual categories for kinds of substances based on functional usage in daily life (similarly to how objects are classified; Lynch & Jones, 1995; Stavy, 1991). For example, Liu and Lesniak (2006) indicated that students of various ages often described substances in terms of their benefits and common use (e.g. water for drinking; baking soda for baking). Bretz and Emenike (2012) described the strong association that some elementary school children built between the concept of 'chemicals,' conceived as a special class of stuff, and materials used for practical purposes, such as cleaning products. Materials known to have similar functions (e.g. glues, oils) were often assumed to share the same intrinsic nature.

Historicality. Novice learners rely on their knowledge about the origin and history of a material to make decisions about both chemical identity and conservation of chemical identity during a process (Johnson, 2000; Krnel, Watson, & Glažar, 2005; Talanquer, 2006). We use the term 'historicality' to refer to the influence of knowledge of origin and past history on current thought about entities of interest (Wandersee, 1992). Existing research suggests that samples of a given substance are often judged to be different if they come from distinct sources or result from different processes. For example, people are known to think differently about natural versus synthetic samples of the same substance (Rozin, 2005). The ability to trace the history of a material influences how learners make decisions about conservation of identity during physical or chemical changes (Krnel, Watson, & Glažar, 2005; Van Driel, 2002). Students often assume that changes that occur naturally, without external intervention, have little or no impact on chemical identity, particularly if modifications in appearance are gradual (i.e. traceable) and somewhat subtle (e.g. as when a piece of metal corrodes; Nieswandt, 2001). On the other hand, novice learners can be expected to make claims about change of identity when processes dramatically alter the appearance or functional usage of the materials under consideration, making them look like members of a different material class (Rahayu & Tytler, 1999; Tytler, 2000). This often occurs in processes involving gases (e.g. evaporating a liquid, burning a paper into ashes), which many novice learners conceive as immaterial entities (Wiser & Smith, 2008).

Surface similarity, functional usage, and historicality play a central role in novice learner's ideas about what types of matter are there and what cues can be used to differentiate them. Initial views of materials are not compositional in nature, in the sense of thinking of materials as the constituents of things. Rather, materials are seen as distinct classes of stuff (e.g. metals, plastics, salts) with different perceivable properties, usages, or origins (Dickinson, 1987; Smith et al., 1985; Vogelezang, 1987). There is no or little recognition of the wide diversity of substances within a class (Solominodou & Stavridou, 2000). At this level, students are likely to use a mixture of extensive (i.e. dependent on size) and intensive (i.e. independent of size) properties to classify materials (Krnel, Watson, & Glažar, 1998, 2005); these cues are likely to be explicit rather than implicit. Which specific cues are used to make judgments about the identity of a material depends on what cues are more salient in a given context, prior knowledge, and personal experience with different materials.

Initial progress

Novice learners' reasoning about the identity of materials, as described in the previous section, is quite different from canonical ways of thinking in modern chemistry. The notion of 'substance' as conceptualized by chemical scientists is difficult to interpret or conceive when students' thinking is constrained by the intuitive assumptions described above, as are the intellectual and experimental strategies used by chemical scientists to infer chemical identity. Existing educational research suggests that the development of these ideas likely takes a long time and it may occur in rather patchy ways, with more sophisticated understandings of some types of materials developing sooner than for others (e.g. solid versus gaseous materials; molecular versus ionic compounds; Dickinson, 1987; Johnson, 2000; Krnel, Glažar, & Watson, 2003). The road toward chemical thinking in this area seems to demand the following shifts in the ways students reason about materials and their properties:

- Students assume that materials or substances are the underlying 'constituents' of objects in their surroundings, rather than simple labels for classes of stuff with common usages, history, or perceptual features (Smith et al., 1985; Wiser & Smith, 2008);

- Students differentiate the properties of a material from those of an object, and start paying increasing attention to implicit intensive properties of materials to categorize them (Krnel, Watson, & Glažar, 1998, 2005; Krnel, Glažar, & Watson, 2003).
- Students recognize the limitations of perception in identifying or distinguishing materials and understand the need for experimental testing of selected differentiating properties (e.g. melting points) of substances that are acknowledged as unknown (Johnson, 2000).

Such shifts in thinking may be considered as 'reconceptualizations', conceived by Wiser and collaborators as a 'deep and fundamental reorganization of the large network of knowledge relevant to understanding' (Wiser et al., 2013, p. 96). Reconceptualizations in this sense are like 'threshold concepts' as conceptualized by Meyer and Land (2006), opening up new and previously inaccessible ways of thinking about something.

These changes in student reasoning are critical for supporting the development of core chemistry concepts such as substance, mixture, chemical change, and chemical analysis. Nevertheless, it is important to acknowledge that such changes may also trigger additional conceptual roadblocks. For example, assuming that materials are the underlying constituents of things may support essentialist views of matter in which core essences are seen as unchangeable (De Vos & Verdonk, 1987; Talanquer, 2006). Materials may be thus conceived as enduring entities whose identity survives through most types of changes (Renström, Andersson, & Marton, 1990). This latter way of thinking has been elicited in a variety of studies involving secondary school science students in various countries (Johnson, 2000; Nieswandt, 2001; Rahayu & Tytler, 1999). Many students in these investigations did not seem to have a mental model that would allow them to explain how substances may change their identity. Thus, in trying to account for observed changes in matter, these types of learners often invoke processes that involve displacement of entities from one location to another, or the mixing or separation of existing components (Andersson, 1986).

Analysis of students' ideas about the properties of materials suggests that many learners may see some properties (e.g. color, taste, smell) as separable from the actual substances (Sanmartí, Izquierdo, & Watson, 1995; Scheffel, Brockmeier, & Parchmann, 2009). They may think of such properties as quasi-material entities that may be added, removed, or become exposed as a result of a process without change in a substance's identity. This tendency to substantialize some properties of matter (substantialization) has been described by various authors (Reiner, Slotta, & Chi, 2000; Taber & García-Franco, 2010). This way of thinking shares similarities with a dominant way of knowing in pre-modern chemistry referred to as *Principlism* (Chang, 2011). In this framework, properties of matter were explained by the presence (or absence) of 'principles' that conferred substances the properties observed experimentally (if substance A had the important characteristic C, then it was assumed that A contained the principle P, which was responsible for C; Langley, Simon, Brandshaw, & Zytkow, 1987). For example, the caloric principle was related to temperature, while the flogiston principle was linked to a substance's combustibility. The transformation of substances was many times explained by the application (or withdrawal) of such principles, without reference to changes in chemical identity.

Students' 'principlist' ideas about the properties of materials can be expected to affect their thinking about chemical identity. For example, these views are likely to hinder their ability to differentiate between single substances and mixtures of substances, particularly when dealing with homogeneous materials (De Vos & Verdonk, 1987; Johnson, 2000; Wiser & Smith, 2008). Learners at this stage may think of a homogeneous entity as a single substance under some circumstances, but as a mixture of several components when trying to explain changes in perceivable properties. Students who think this way are also likely to assume that such perceivable properties are the result of the weighted average of the properties of individual components (additivity), rather than emerging from their dynamic interactions (Taber & García-Franco, 2010; Talanquer, 2008). In consequence, they may be misguided during identification or differentiation tasks by the presence of properties that they attribute to particular components (Andersson, 1986; Talanquer, 2013). With proper interventions, students can learn to recognize that single substances exhibit behaviors that differ from those of homogeneously mixed materials (e.g. constant versus varying melting temperatures; Johnson, 2000), and that new properties may emerge from interactions among components (Solominodou & Stavridou, 2000).

Transitioning from Macro to Submicro Views

During their secondary school years, many students around the world are introduced to the particulate model of matter in their chemistry courses. The model is commonly used to explain the physical properties of generic forms of matter represented as collections of de-identified particles. Research on student learning in this area, although vast, provides little insight into the evolution of students' ideas about chemical identity. Nevertheless, at this stage most learners also learn about the existence of chemical elements and compounds, and are introduced to the symbols [e.g. $NaHCO_3(s)$, CH_3COO^- (aq), and Cl_2 (g)] and icons (e.g. small circles in boxes as two-dimensional visualizations of molecule arrangements in different phases) used to represent their composition and structure at the submicroscopic level (atomic-molecular model of matter). Typically, the introduction of these topics involves a major shift in educational focus, from having students analyze real materials to having them interpret chemical representations, and from focusing the attention on measurable properties as differentiating characteristics to learning to rely on explicit and implicit cues conveyed by symbolic and iconic representations.

Most existing research on students' ideas about the atomic-molecular model of matter related to issues of chemical identity has focused on the analysis of students' ability to identify or differentiate among major types of matter such as: elements, compounds, and mixtures (Briggs & Holding, 1986; Kind, 2004; Sanger, 2000; Stains & Talanquer, 2007); molecular (covalent) and ionic compounds (Taber, 2002); polar and non-polar substances (Furió, Calatayud, Bárcenas, & Padilla, 2000); or acids and bases (Furió-Más, Calatayud, & Bárcenas, 2007; Ross & Munby, 1991). Despite the existence of different topic-specific challenges in the analysis of these various types of substances, research findings elicit common trends in student reasoning when facing identification or classification tasks using chemical representations. In particular, many students tend to reduce the complexity of the tasks by using a single cue or attribute to differentiate among represented substances. Most salient cues to novice learners tend to be explicit attributes (e.g. differences in the number of atoms present in chemical formulas) rather than implicit features (e.g. type of chemical bonding). The selected cues are more likely to be compositional than structural in nature, and their selection is often guided by strong mental associations between certain representational features and specific properties or types of materials. For example, many students associate the words element-atom and compound-molecule, and thus they tend to think of all chemical elements as atomic and of all chemical compounds as molecular (Stains & Talanquer, 2007; Taber, 2002). Other students have built strong associations between the presence of an H (or OH) symbol and acidic (or basic) behaviors (Furió-Más et al., 2007). Additionally, many learners fail to differentiate between some concepts, such as compound and homogeneous mixtures (Sanger, 2000), or bond polarity and molecular polarity (Furió et al., 2000), which leads them to make inaccurate and inconsistent categorization decisions.

Students' difficulties in selecting proper and productive cues in the identification and differentiation of chemical substances have been elicited at different educational levels, and seem to persist with training in the discipline. Challenges in differentiating between elements and compounds (Kind, 2004; Stains & Talanquer, 2007) or between substances with different acid–base properties (Cartrette & Mayo, 2011; McClary & Talanquer, 2011) have been reported in studies involving secondary school, undergraduate, and graduate students in chemistry. Research findings indicate that the critical attributes used by many students to make categorization decisions are not necessarily stable, and may change depending on the types of substances under analysis or the nature of the chemical representations. Learners struggle to discriminate relevant from irrelevant features, and their reasoning is highly influenced by the content being discussed in the classroom. For example, organic chemistry students have been found to rely on the more explicit features, such as atom connectivity or the presence of certain functional groups, when classifying represented compounds, but increase their reliance on implicit features such as stereochemistry as such topics become relevant in the curriculum (Domin, Al-Masum, & Mensah, 2008).

Students' reasoning about chemical substances at the submicroscopic level is highly influenced by the same types of assumptions that learners make about properties and behaviors at the macroscopic level (Talanquer, 2006). For many students, the different types of atoms that make up a substance are ultimate carriers of the properties that we observe (elementalism). In this view, the atoms-elements become the 'principles' responsible for observed behaviors. Students tend thus to think of substances as mixtures of atoms-elements with characteristic properties (*compositionism*) that get added in a simple fashion (additivity) to generate the macroscopic features that we observe

(Taber & García-Franco, 2010; Talanquer, 2008). To a great extent, a critical problem for many students is that they still think of substances as static objects made up of combinations of small parts with fixed structures and properties. A more productive conceptualization would be to think of substances as dynamic entities (i.e. processes), with stable properties that emerge from the interactions of its components (*interactionism*). In this view, density, melting point, and solubility are emergent properties of matter resulting from the interactions of myriads of particles at the molecular level, while chemical properties of single molecules emerge from interactions among subatomic components. From this perspective, chemical identity is better explored by paying attention to such interactions and the factors that affect them, rather than just focusing on the nature of individual components. Students' difficulties to develop an emergent view of properties and processes of matter have been described by different authors (Chi, Roscoe, Slotta, Roy, & Chase, 2012; Talanquer, 2008). Emergence can thus be recognized as another important threshold concept in the path to developing normative ideas about chemical identity.

Discussion and Implications

The core results of our analysis are summarized in Figure 1. This figure intends to represent what we identify as major cognitive attractors for how students conceptualize materials and think about the factors that affect their identity. The figure seeks to highlight likely overlapping assumptions about chemical identity, some of which become less or more dominant as learners progress in their studies. Our findings suggest that students' ideas about chemical identity evolve with training in the discipline, but developing normative understandings may require considerable scaffolding. Specific suggestions in this regard are introduced and discussed below.

While Figure 1 represents a map that summarizes our analysis of the landscape of conceptual sophistication in thinking about chemical identity, it is important to point out that there are limits to how to interpret this representation. The map does not imply, for example, that students' reasoning progresses in a linear fashion from the less to the more sophisticated assumptions highlighted in the figure, nor that progression occurs at the same pace along each of the three threads. Neither do we contend that individual assumptions (e.g. historicality, functional usage) that we represent as clustered around a major pattern of reasoning (e.g. objectivization) do not influence student thinking as students' ideas about materials become more sophisticated. In fact, existing evidence suggests that historicality and surface similarity play a central role in how many individuals who have principlist or compositionist views of substances make judgments about conservation of chemical identity during a process. Similarly, students may hold principlist assumptions about some properties of materials, such as color, while expressing interactionist assumptions about other properties, such as melting point.

A detailed description of a hypothetical progression of students' ideas about chemical identity is difficult to build for a variety of reasons. First, learners do not seem to have a monolithic view about the nature, composition, and properties of the various types of materials they encounter in their daily lives. Thus, ideas about different classes of substances may evolve in different manners depending on prior knowledge and personal experiences with particular types of matter. Second, existing research on students' ideas related to chemical identity is somewhat spotty. Studies involving novice learners are more abundant than those focused on students enrolled in more advanced chemistry courses. Finally, dominant chemistry curricula at different educational levels are not designed to foster a gradual and meaningful development of the concept of chemical identity. The study of kinds of materials frequently undergoes dramatic shifts in framework with the introduction of the particulate model of matter, when the attention moves from differentiating matter types based on comparison of measurable properties to first explaining generic behaviors (e.g. phase changes, compressibility, diffusion) using identity-less particles, and then making distinctions between substances based on symbolic features of their representations. These shifts often occur before learners have a chance to develop a solid understanding of ways of thinking about chemical substances within each framework.

We believe that a more gradual, systematic, and coherent approach to teaching and learning about chemical identity would greatly benefit students at all educational levels. It would help them better organize and integrate the complex knowledge system (Carey, 2009; Vosniadou, 1994) from which the idea of chemical identity emerges, including a meaningful understanding of core chemistry concepts, such as chemical substance and chemical reaction, and central chemistry practices, such as chemical analysis. Our results shed light on the nature of such an educational approach as it would have to scaffold and support student learning through the progression of assumptions summarized in Figure 1, helping learners develop the threshold concepts highlighted in our findings. In line with suggestions from other authors about changes to traditional approaches to the teaching of core chemistry concepts (Johnson & Papageorgiou, 2010), such educational reform would demand a change in the conceptual framework in which the particulate model of matter is introduced, as well as careful consideration of how to build bridges between macroscopic, particulate, and atomic conceptualizations of different materials. In general, this new frame demands exploring materials using a 'chemical lens' in which the goal is not only to develop explanatory accounts about generic properties and behaviors, but to differentiate and synthesize specific matter types. In the following paragraphs we describe some of the critical elements that such reconceptualization of chemistry education may include.

At the core of our proposal is the idea that chemistry instruction should be driven by the search for answers to essential questions in the discipline (e.g. What is this made of? How do I make it?), rather than by the intent to cover a set of core topics in the field (e.g. atomic structure, chemical bonding; Talanquer & Pollard, 2010). Such quests for answers should be aimed at helping students develop meaningful understanding of crosscutting disciplinary concepts (e.g. chemical identity), through direct engagement in core disciplinary activities (e.g. investigation, design, evaluation) in relevant and authentic contexts (Sevian & Talanquer, 2014). This engagement should be carefully planned and scaffolded to help students reach conceptual stepping stones on the road toward more sophisticated understandings (Wiser & Smith, 2008). Instruction should also provide students with mechanisms for knowledge restructuring, such as model-based and analogical reasoning, and should pay attention to the development of metacognitive skills (Vosniadou, Vamvakoussi, & Skopeliti, 2008). This type of instruction demands considerable social support based on collective dialogue and argumentation (Hatano & Inagaki, 2003).

The findings of our study suggest that the construction of the concept of chemical identity could start by helping students move away from thinking of materials as objects and classes of stuff ('objectivization' in Figure 1) to recognizing them as the constituents of things. As suggested by others (Krnel, Glažar, & Watson, 2003; Wiser et al., 2013), this could be accomplished by engaging young children in the analysis of objects of different sizes and shapes made of the same or different materials. Educational activities could involve labeling, describing, and categorizing these objects, comparing and contrasting perceptual properties to help students differentiate the concepts of object and material. Further analysis could involve acting on objects by cutting, crushing, and grinding them to compare and contrast whole-part properties and scaffold the conceptual differentiation of extensive and intensive properties. The central educational goal at this level should be to help students recognize the limitations of *objectivization* when trying to differentiate kinds of substances, and develop the idea of materials as constituents of objects.

Students should be guided to recognize that there are intensive properties that can be used to differentiate materials, independently of the nature of the sample at hand. A critical idea to develop is that the most effective differentiating characteristics tend to be properties that provide information about how the material responds to changes in conditions that we can control experimentally (they could be called 'response properties'). In particular, we want students to recognize that characterizing substances demands experimental testing (Johnson, 2000), and that common testing strategies involve the analysis of how materials respond to energy transfer or to the presence of other materials. This central idea could serve as a major thread in organizing core pieces of chemistry curricula within and across grade levels. For example, one could conceptualize a curricular sequence in which learners first engage in trying to differentiate materials by testing mechanical properties (i.e. properties that measure how materials respond to the action of forces or mechanical work, such as elasticity and compressibility). In a second stage, students could explore identification strategies based on the analysis of thermal properties (i.e. properties that measure how materials respond to changes in temperature, such as heat capacity and melting point). Comparison of melting and boiling points behavior could be used to not only highlight techniques to differentiate substances, but also determine whether a material is a single substance or a mixture of several components (Johnson, 2000). Further exploration of, for example, electrical properties (i.e. properties that measure how materials respond to changes in an electric field, such as conductivity) could be used to differentiate important classes of substances, such as ionic and molecular compounds. Overall, we want students to recognize that chemical identity is better explored and judged by analyzing how substances respond to diverse interactions than by paying attention to surface features, origin, or material history.

A focus on analyzing how different materials respond to external changes in temperature, pressure, or electrical field would elicit the non-additive behavior of many physical properties in systems comprised of two or more components. It would also make explicit that changes in physical appearance are not necessarily indicative of changes in chemical identity. The search for different 'response properties' that are effective and efficient in answering analytical questions in different contexts can also be used to sequence instruction within and across grade levels in a manner that naturally demands increased sophistication in modeling the nature of matter. Engaging pupils in using, evaluating, and generating submicroscopic models of matter seems to be critical in helping students develop more sophisticated views of physical (Chi et al., 2012) and chemical (Johnson & Papageorgiou, 2010; Wiser & Smith, 2008) processes that go beyond relying on principlist or substantialist assumptions (Figure 1) to explain change.

For example, as students begin to explore different materials by testing their mechanical or thermal properties, they can be asked to engage in modeling activities looking to generate models of matter that may explain differences in observed behaviors. These types of activities can begin in early grades. Existing research suggests that, with proper scaffolding, elementary school students can successfully develop particulate models of matter to explain changes in materials due to mechanical action (Acher, Arcà, & Sanmartí, 2007). These models would have to be revised in order to make sense of experimental data resulting from the analysis of other types of response properties, such as differences in melting points or electrical conductivity in solution. The introduction to response properties that are chemical in nature, such as solubility and chemical reactivity, could open the door to transition from explanations based on the particulate model of matter to explanations that require assumptions about atomic-molecular composition and structure. At more advanced stages, exploration of analytical techniques based on light–matter interactions (i.e. how substances respond to electromagnetic radiation) naturally sets the stage for discussions about subatomic models of matter.

The above educational approach demands that we reflect on how best to help students build connections between macroscopic experiences and submicroscopic models of matter, scaffolding the development of an interactionist view of matter. Students should be led to understand that differences in mechanical, thermal, and electrical response properties can be explained by using a basic particulate model of matter involving dynamic collections of interacting particles that differ in the nature and strength of interparticle interactions. Educational interventions like those proposed by Chi and collaborators (2012) designed to develop an 'emergent' view of dynamic processes may be useful in this area. On the other hand, making sense of differences in chemical properties is facilitated with atomic-molecular models in which distinctive interparticle interactions can be attributed to differences in atomic composition and structure. In this case, emphasis should be put on developing understanding of how molecular properties emerge from interactions at the atomic level, comparing and contrasting the power of these ideas to additive views of atomic properties ('compositionism' in Figure 1). Once the importance of characterizing atomic composition and molecular structure is recognized, discussion can focus on the types of experimental techniques that allow us to explore matter at that level (e.g. emission and absorption of spectroscopy). Interpretation of the associated experimental data relies on models of matter that relate light–matter interactions to structural and energetic factors at the electronic level. As we can see, development of student understanding of chemical identity issues requires the parallel and interconnected development of ideas at various scales, from macroscopic to multiparticle to molecular to atomic. Figure 2 seeks to summarize the core aims, foci, and modeling scales of a curricular progression based on these ideas.

Based on our analysis, and in agreement with educational models suggested by other authors (Eilks, 2013; Johnson & Papageorgiou, 2010), we believe that chemistry education would benefit from a reconceptualization of conventional ways of introducing and developing ideas about the particle theory of matter. This change in conceptual framework should involve rethinking both curricular sequence and focus. In dominant educational approaches, progression of understanding about the nature of matter is often conceptualized as moving from macroscopic to particulate to atomic to subatomic descriptions in a serial manner (NRC, 2011, 2013; Stevens, Delgado, & Krajcik, 2010). As discussed in previous paragraphs, our view is that meaningful learning about chemical identity and related core chemistry concepts might be better facilitated by fostering sophisticated reasoning at the macroscopic

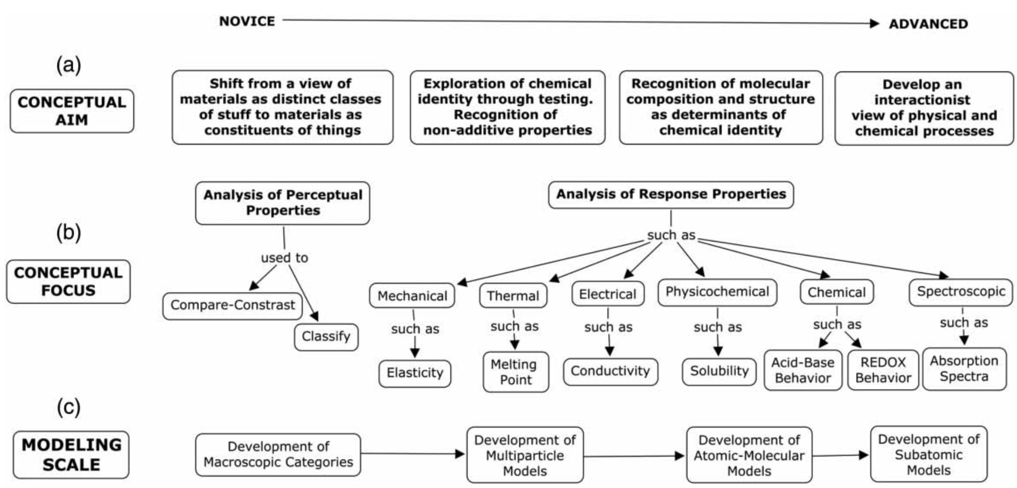

Figure 2. Suggested curricular sequence designed to foster students' conceptual understanding of chemical identity at the macroscopic and submicroscopic levels. We highlight the major (a) conceptual aims of the proposed instructional interventions in relation to the assumptions summarized in Figure 1, (b) conceptual foci of associated educational activities, and (c) scale of modeling matter in which students engage to foster conceptual progression in their understanding of chemical identity

and submicroscopic levels in a parallel and coordinated manner. This could be accomplished by using instructional models that emphasize macro–micro thinking through authentic chemistry practices (Van Berkel, Pilot, & Bulte, 2009). Second, traditional ways of introducing students to the particle theory of matter involve the use of models to explain physical properties (e.g. solidity, liquidity, compressibility) and behaviors (e.g. diffusion, phase changes). The central goal in this framework is to help students develop explanatory accounts about physical properties and phenomena independently of the nature of the materials under consideration. The shortcomings of this approach have been highlighted by other authors (Johnson & Papageorgiou, 2010). From a chemical perspective, a more productive approach would be to engage students in building models of matter seeking to explain differences in the behavior of different chemical substances. Students' attention could then be directed to reflect on those features that are most relevant in differentiating materials, such as particle size and shape, and the nature and strength of interparticle interactions. Then, the intellectual quest would be to revise such models to account for differences in submicroscopic characteristics, as well as to build explanations for differences in diverse response properties, from physical to chemical to spectroscopic behaviors.

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