Science & Education (2020) 29:1317–1360
https://doi.org/10.1007/s11191-020-00152-4

ARTICLE

Conceptual Profile of Substance

Representing Heterogeneity of Thinking in Chemistry Classrooms

Raúl Orduña Picón[1] · Hannah Sevian[1] · Eduardo F. Mortimer[2]

Published online: 12 September 2020

Abstract
Teachers face challenges when building the concept of substance with students because tensions of meanings emerge from students' daily life and canonical ideas developed in classrooms. A powerful tool to address learning, pedagogical, and research challenges is the conceptual profile theory. According to this theory, people employ various ways of conceptualizing the world to signify experiences. Conceptual profiles are models of the heterogeneity of modes of thinking and speaking about a given scientific concept which are used in a variety of contexts. To better understand the heterogeneity of thinking/speaking about substance, the present study aimed to answer: (1) What are the zones that constitute the conceptual profile of substance?; and (2) What ways of thinking and speaking about substance do teachers and students exhibit when engaged in a classroom formative assessment activity? The study adopted an inductive–deductive qualitative analysis approach to analyze secondary data from the history of chemistry, philosophy of chemistry, and student thinking, as well as primary data from student and teacher questionnaires and interviews in eight classrooms, and a formative assessment activity in four of these classrooms. Six conceptual profile zones were found through identifying sets of ontological, epistemological, and axiological commitments regarding each zone. Subsequently, the conceptual profile of substance was tested by employing it to re-analyze the formative assessment activity to represent high school students' and teachers' thinking about substance. The developed conceptual profile was found to be effective, thus prospectively useful to teachers, in representing the heterogeneity of thinking about substance in chemistry classrooms.

Keywords Substance · Conceptual profile theory · Ontological · Epistemological · And axiological commitments

✉ Hannah Sevian
hannah.sevian@umb.edu

[1] Department of Chemistry, University of Massachusetts Boston, Boston, MA, USA

[2] Faculdade de Educação, Universidade Federal de Minas Gerais, Belo Horizonte, Brazil

1 Introduction

Chemistry, as a *technoscience* (Chamizo 2013), is a practice that entails the identification, analysis, modeling, and syntheses of substances, as well as the evaluation of the benefits, costs, and risks of the use, production, and transformation of those substances (Sevian and Talanquer 2014). It is a discipline ontologically grounded in the concept of substance (hereafter called *substance* instead of *concept of substance*) because, in order to perform their practice, chemists treat substance either as a theoretical or an empirical entity to understand and act upon the reality; however, substance is ultimately conceived as an idealized entity (Fernández-González 2013; Suppe 1989; van Brakel 2014). Based on its relative different ontologies (i.e., empirical, theoretical, or idealized entity), substance can be seen as a polysemous word which has a variety of meanings depending on the context of use.

Chemists are not the only individuals who have different views of substance as they make sense of the world. Chemistry students also generate a variety of ways of thinking and talking about substance through having experiences with them in formal instruction (e.g., chemistry laboratory) and informal settings (e.g., home). The word chemical is commonly brought to both formal and informal settings by learners in order to refer to a given substance. When chemistry students use the word chemical, they usually exhibit ways of talking that reflect the idea that substances are utilized for the benefit or hazard of human beings (Bretz and Emenike 2012). Also, students' experiences in handling and manipulating substances mainly contribute to the formation of a system of differentiation and classification of substances based on observable characteristics (Ngai et al. 2014; Ngai and Sevian 2017; de Vos and Verdonk 1987).

A challenge that chemistry teachers face when building the concept of substance with their students is the tension between what students know from daily life and the scientific ideas developed in chemistry classrooms. This often results in chemistry teachers considering prior knowledge and canonical understanding as a dichotomy that can be addressed by the idea of conceptual replacement: students should abandon their prior ideas to move toward scientific understandings (Hewson 1981). Despite calls to shift from a "fix it" to a "work with it" perspective (Duschl et al. 2011), chemistry teachers rarely conceive this tension as a continuum where multiple modes of conceptualizing substance coexist to function as a repertoire of views for making sense of phenomena. Evidence of the dichotomous view is that chemistry teachers themselves demonstrate ways of speaking that are similar to the ways that students talk about substance in their daily lives. Salloum and BouJaoude (2008) found that, when asked to give examples of substances, secondary chemistry teachers provided only substances such as additives or substances found in a laboratory which tended to serve a purpose. Chemistry teachers may not realize that the meaning-making process about substance is complicated by the fact that the word, by itself, does not have a unique meaning. These divergences can be addressed by recognizing that both everyday and scientific thinking, as well as ways of thinking that give rise to what are often recognized as misconceptions, are part of the students', as well as teachers', repertoires that can be productively used in different contexts.

Learning substance entails a dialogical process, that is, a process of bringing together and working on diverse ideas (ongoing process of comparing and checking our own understanding with the ideas that are brought through social interaction) in order to recognize domains of productive explanations and, within such domains, to be able to use them (Mortimer and Wertsch 2003). This is aligned with Vogelezang (1987, p. 243): "What aspects of a concept of a substance are important for making it useful in the context of school chemistry? The answer depends on what the concept is to be used for." This capacity enables students to formulate, in cooperation with each other and their teacher, which aspects are relevant to the desired concept of substance and which are not (Vogelezang 1987). The challenge for chemistry teachers and students, as well as science and chemistry education researchers, relies on constructing a critical perspective in order to discern the use of particular ways of thinking about substance through being aware of the limitations and powers of these ways of thinking in different social contexts (e.g., a chemistry classroom, a supermarket, etc.).

A powerful tool to better address these learning, pedagogical, and research challenges is the conceptual profile theory (Mortimer 1995; Mortimer and El-Hani 2014). The conceptual profile theory is grounded in the idea that every person has her or his own ways of seeing and conceptualizing the world to signify experiences in different contexts. Conceptual profiles are models of the heterogeneity of modes of thinking which are used in a variety of contexts by people with a given cultural background (Mortimer et al. 2012; Mortimer and El-Hani 2014). They are composed of several conceptual profile zones. Each zone represents a particular mode of thinking associated with a characteristic mode of speaking. Conceptual profile zones are stabilized by socially constructed ontological, epistemological, and axiological commitments that shape each individual's ways of thinking and speaking in different contexts. In this way, "stabilized" means that a zone of a concept is general and relatively fixed enough that individuals who have different senses of a word still use that word with the same meaning.

Because conceptual profile zones are contextually dependent, a variety of contexts should be explored to identify the ontological, epistemological, and axiological commitments that stabilize each way of thinking and speaking. The characterization of conceptual profile zones provides teachers with a resource for working with students' and their own ways of thinking, to differentiate and strengthen various zones, as well as to introduce new zones in students' conceptual profiles, and to help students learn to recognize situations in which different zones can be productively relied upon to make sense of phenomena at real-world, quasi-ideal, and ideal levels. The characterization of conceptual profile zones of a given concept is also key for understanding the pluralism of individuals' talk because it has been demonstrated that individuals, science students and scientists, can speak in ways that are consistent with multiple zones (Aguiar et al. 2018; Amaral et al. 2018; Mortimer and El-Hani 2014).

According to the sociocultural perspective, when studying the ways in which people think about specific ideas in science, the starting point is to investigate the ways in which they talk in different contexts (Mortimer and Wertsch 2003). In the present paper, conceptual profile theory is used as the theoretical framework that justifies the exploration of different ways of speaking and thinking about substance. Then, the method that was employed to build the conceptual profile of substance (a model to represent multiple ways of thinking about substance) is described in order to illustrate how the different ways of speaking and thinking about substance were sought and identified. Next, each way of thinking about substance that was found is shown through pointing out the set of commitments that makes it unique from the other ways of thinking. In addition, an analysis of the different ways of thinking about substance that were identified from implementing a formative assessment in four chemistry high school classrooms is presented to demonstrate the applicability of the conceptual profile of substance as either a pedagogical tool (to notice and interpret students' ways of speaking and thinking about substance in chemistry classrooms) or as a research tool (to characterize and portray the degree of heterogeneity in ways of thinking about substance in chemistry classrooms).

Also, some difficulties in analyzing the data for particular ways of thinking are highlighted as entry points for future improvements about the exploration of zones in multiple contexts. The following questions drive the present study:

- What are the zones that constitute the conceptual profile of substance?
- What ways of thinking and speaking about substance do teachers and students exhibit when engaged in a classroom formative assessment activity?

Thus, the purpose of the present paper is to elicit, identify, characterize, and portray different ways of speaking and thinking about substance that can contribute to (1) the philosophical understanding of the polysemy that this concept in chemistry carries, and (2) the practical foundation for science teachers in general, and chemistry in particular, to shift to an asset-based ("work with it") approach to teaching substance.

1.1 Modeling Learning about Substance and the Conceptual Profile Theory

One of the most common ways chemistry is introduced in textbooks, social media, classrooms, etc., is through saying chemistry is everywhere. This omnipresence is mainly justified through conceiving that all substances and their interactions with other substances and energy make possible human life. How people make sense of and experience substances has been an important area of research in science and chemistry education to better understand the impact of individuals' everyday and canonical ideas in their own conceptualization of the concept. Two frameworks that have embodied a developmental approach to learning the concept of substance are learning progressions (Ngai et al. 2014; Ngai and Sevian 2017) and conceptual profile theory (CPT) (Amaral et al. 2018; Silva and Amaral 2013).

Through robustly exploring and interpreting secondary data in the history and philosophy of chemistry, as well as published studies about students' alternative conceptions related to substance, materials, and matter, Ngai et al. (2014) proposed a hypothetical learning progression about how substances are conceptualized and what factors affect their identity. They identified four cognitive attractors (objectivization, principlism, compositionism, and interactionism) that are stabilized ways of thinking about substances/materials based on particular assumptions. They recognize that the learning progression of chemical identity is not a merely linear path of increasing conceptual sophistication in thinking from less to more sophisticated assumptions, nor does progression in thinking follow a particular stride along the cognitive attractors. They also consider that assumptions that are less sophisticated than complex ones do not negatively impact student thinking. However, their main suggestion is that their learning progression can assist teachers to support students to move from less toward more sophisticated thinking to develop a more powerful concept of chemical identity. What Ngai et al. (2014) assume is that the more sophisticated assumptions have a pragmatic value per se when students aim to solve problems in different contexts; i.e., those ways of thinking often have inherent powers that make them more productive in understanding chemistry than simpler thoughts such as many in everyday ideas. However, several researchers (Aguiar et al. 2018; Dawson 2014; Driver et al. 1994) have demonstrated that people consciously or unconsciously select a specific way of thinking, among several options, when making sense about an experience/phenomenon in a particular situation, and the scientific idea is not always the most productive. Therefore, it is the sociocultural context (who is interacting with whom, where this interaction is occurring, what the purpose of this interaction is, etc.) that constrains what ways of thinking individuals consider the most convenient to use (Sikorski 2019). As Ngai et al. (2014) point out: “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 lives. Thus, ideas about different substances may evolve in different manners depending on prior knowledge and personal experiences with particular types of matter” (p. 2452).

While a conceptual profile may be relatively stable for a group of people in a particular society at a certain point in history, each individual in that group likely has a different expression of the conceptual profile zones. That is, individuals have unique profiles that depend on their own experiences and how they make sense of a concept in specific contexts and based on their own experiences and cultural backgrounds, and there are also *supra-individual* systems of thinking and speaking that are the common zones expressed in a population. CPT aims to document, characterize, and portray the supra-individual systems of thinking and speaking—the conceptual profile of a concept—with the intention that this can help to understand the ways that individuals conceptualize that concept. CPT is grounded in the idea that every person has his or her own ways of conceptualizing the world to make sense of experiences in different contexts (Mortimer 1995). Conceptual profiles are models of the diversity of modes of thinking and speaking about a given polysemous concept that are used in a variety of contexts by people with a particular cultural background (Mortimer and El-Hani 2014); they are composed of several conceptual profile zones. Each conceptual profile zone represents a particular way of thinking associated with a characteristic way of speaking. Conceptual profile zones are stabilized by socially constructed ontological, epistemological, and axiological commitments that constrain each individual’s ways of thinking and speaking in different contexts. The distinction between sense and meaning is useful in establishing a clear view of what stability means in ways of speaking and thinking about a concept. For Vygotsky (1987), the *sense* of a word is dynamic, fluid, and quite personal; while *meaning* is relatively general and more fixed in a larger group of people. A word’s meaning allows the possibility that two or more people can share a particular meaning of a word, even though they may attribute different senses to it. The stability of ways of thinking and speaking of a word emerges from using that word with a generalizable meaning in social interactions, instead of a personal sense. Thus, to identify the different ways of speaking and thinking about a given concept, it is necessary to look for concepts that have been generalized by social discourse within the constraints of what is plausible in a sociocultural frame.

Because conceptual profile zones are contextually dependent, a variety of contexts should be explored to identify the ontological, epistemological, and axiological commitments that stabilize each way of thinking and speaking. Vygotsky’s genetic method (Wertsch 1985) provides a framework for understanding the genesis of a concept through the exploration of three genetic domains: (1) the sociocultural domain—related to how the understandings about a concept evolved through the history of mankind; (2) the ontogenetic domain—based on how a concept is learned and evolved through the history of each individual; (3) the microgenetic domain—associated with how a concept is built within moment-to-moment interactions and expression of ideas during a relatively short period of time.

Silva and Amaral (2013) proposed the first version of a conceptual profile of substance mainly constructed from an exploration of the sociocultural domain through interpreting secondary data related to the concept of substance from the history of chemistry. The study of the ontogenetic domain was carried out through looking into published research in students’ alternative ideas about substance; however, this analysis was one step removed from comparing with the preponderance of data in the sociocultural domain. Finally, relatively less attention was paid to exploring the microgenetic domain, which consisted of the production of empirical data from asking 72 high school and 17 senior undergraduate Brazilian students to answer a questionnaire. The questionnaire contained 9 questions such as "List at least 5 examples of chemical element, substance, and materials and justify your answer," "Do you disagree or agree with the Aristotelian view of elements and substance? Explain whether that view is similar to the contemporary view about substance," and "Substances have their own characteristics. Can we consider that a substance has its own properties under any temperature and pressure?" A subgroup of these participants was interviewed in order to explore follow-up questions to better understand their ideas. Although these questions clearly aimed to elicit students' ways of speaking about substance, they led students toward scientific ways of speaking and provided them few entry points for sharing everyday ideas that are common in daily contexts.

Five zones constituted this first version of the conceptual profile of substance (essentialist, generalist, substantialist, rationalist, and relational). To propose these conceptual profile zones, the authors started with ontological and epistemological commitments that belonged to several zones of different conceptual profiles such as molecule (Mortimer and Amaral 2014), atom (Mortimer 1995, 2000), and heat (Amaral and Mortimer 2001), as well as the exploration of the genetic domains mentioned earlier were considered as initial options that may be present in zones that represented multiple ways of thinking about substance. However, paying more attention to the sociocultural domain, specifically the history of chemistry rather than the ontogenetic and microgenetic domain, led to the construction of an epistemic conceptual profile of substance; i.e., the conceptual profile of substance that Silva and Amaral (2013) constructed was mainly grounded in the general description of practices that have contributed to the development of substance as a concept developed over centuries. Each conceptual profile zone is classified as scientific or not-scientific based on the judgment that ontologies are scientifically justified. In other words, past epistemologies are evaluated based on the current canonical scientific practices that approve or refuse claims. Indeed, this strong orientation toward the epistemology of the concept of substance can be observed in the names and descriptions that some of the zones had, such as generalist, rationalist, and relational, which belong to philosophical schools of thought, and refer to Bachelard's epistemological profile of mass (Bachelard 1973).

Furthermore, some of the commitments that stabilize the conceptual profile zones were ambiguous to differentiate the unique ontological and epistemological commitments that characterize each zone. For instance, the ontological commitment that stabilizes the relational zone is "abstract ideas" (p. 63), which provides insufficient specificity. It can be claimed that all ideas are abstract, but the difference is the level of abstraction that requires to make them tacit and then conceptualize them. On the other hand, axiological commitments (Mattos 2014) were defined as the third dimension that stabilizes ways of thinking and speaking in the conceptual profile theory, but they were not explored at the time of the study by Silva and Amaral (2013) since it was completed prior to the development of axiological commitments as part of CPT. Therefore, while the epistemological commitments of each conceptual profile zone were clearly delimited, the ontological and axiological commitments needed to be clarified, made more accessible, and integrated to better understand the three commitments (ontological, epistemological, and axiological) that stabilize individuals' ways of thinking and speaking about substance. In other words, there was a need to propose a conceptual profile of substance grounded in the plurality of the three genetic domains (sociocultural, ontogenetic, and microgenetic), and the dialogical analysis of the different ways of conceptualizing substance found in each domain to identify the three commitments (ontological, epistemological, and axiological) that stabilize individuals' ways of thinking and speaking about substance.

Amaral et al. (2018) refined the first version of the conceptual profile of substance through adding, merging, and removing zones. Six zones resulted from this refinement process: generalist, pragmatic/utilitarian, substantialist, empirical, rationalist, and relational. However, only the pragmatic/utilitarian zone was found to be stabilized by all three dimensions (ontological, epistemological, and axiological commitments) in this second version of the conceptual profile, while the other five zones were described with explicit epistemological and ontological commitments. While the 2018 study advanced the characterization of the conceptual profile of substance, ambiguity remains in detecting substantial differences among the zones. Also, the process of refining the 2013 version of the conceptual profile of substance was not addressed by Amaral et al. (2018); this generated a new research demand to better understand the construction of the conceptual profile of substance through the identification of sets of ontological, epistemological, and axiological commitments that stabilize each conceptual profile zone.

Based on the research needs and the sake of advancing the conceptual profile of substance, we extend the exploration of the three genetic domains beyond the work of Silva and Amaral (2013) and Amaral et al. (2018). As the prior work focused largely on the sociocultural genetic domain (specifically the history of chemistry), this new work adds what the philosophy of chemistry has to say about the concept of substance, and what ontologies, epistemologies, and axiologies emerge from looking into these secondary sources of data. Regarding the ontogenetic domain, an exhaustive and more rigorous exploration is carried out, building upon what Silva and Amaral (2013) and Amaral et al. (2018) found, to better identify the commitments that stabilize individuals' ways of thinking and speaking about substance. The main goal of this new exploration is to analyze the three genetic domains in a more dialogical manner to better identify the ontological, epistemological, and axiological commitments that stabilize the conceptual profile zones of substance.

With basis in the microgenetic domain, we designed and implemented instruments to better elicit both everyday and scientific ideas, in order to better capture the heterogeneity of thinking about substance. The present study also examines a culture and geography different from the prior work, which is most easily characterized by its different demographics (in this case, American students and teachers). This opens the possibility to find different ways of speaking and thinking than those that have been reported in the two previous studies of the conceptual profile of substance. For instance, a Brazilian student might think about substance based on the traditional uses that a substance might have in a traditional community, while a student in the USA might think about substance as something man-made considering the extensive chemical industries that exist in this country. This difference is justified by conceiving CPT as grounded in the idea that ways of thinking and speaking are dependent on people's cultural backgrounds, thus it is possible that the conceptual profile found in our study differs from the previous studies. The present study also attempts to differentiate the zones through explicitly clarifying the set of commitments that stabilizes each zone. The present study specifically addresses the axiological commitments that are fundamental to be elicited and characterized, which supports Mattos' (Mattos 2014) proposal that axiologies shape both thinking and speech.

2 Methodology

The study adopted an inductive–deductive analysis approach based on the general guidelines of building conceptual profiles (Aguiar et al. 2018; Amaral et al. 2018; Freire et al. 2019; Mortimer and El-Hani 2014) which have been proposed to identify, characterize, and portray heterogeneity of thinking in core concepts in science. This general approach was adapted and employed (see Fig. 1) to analyze secondary data from the history of chemistry, philosophy of chemistry, and student thinking, as well as primary data from student and teacher interviews and a formative assessment activity in chemistry classrooms. The goal was to find out the set

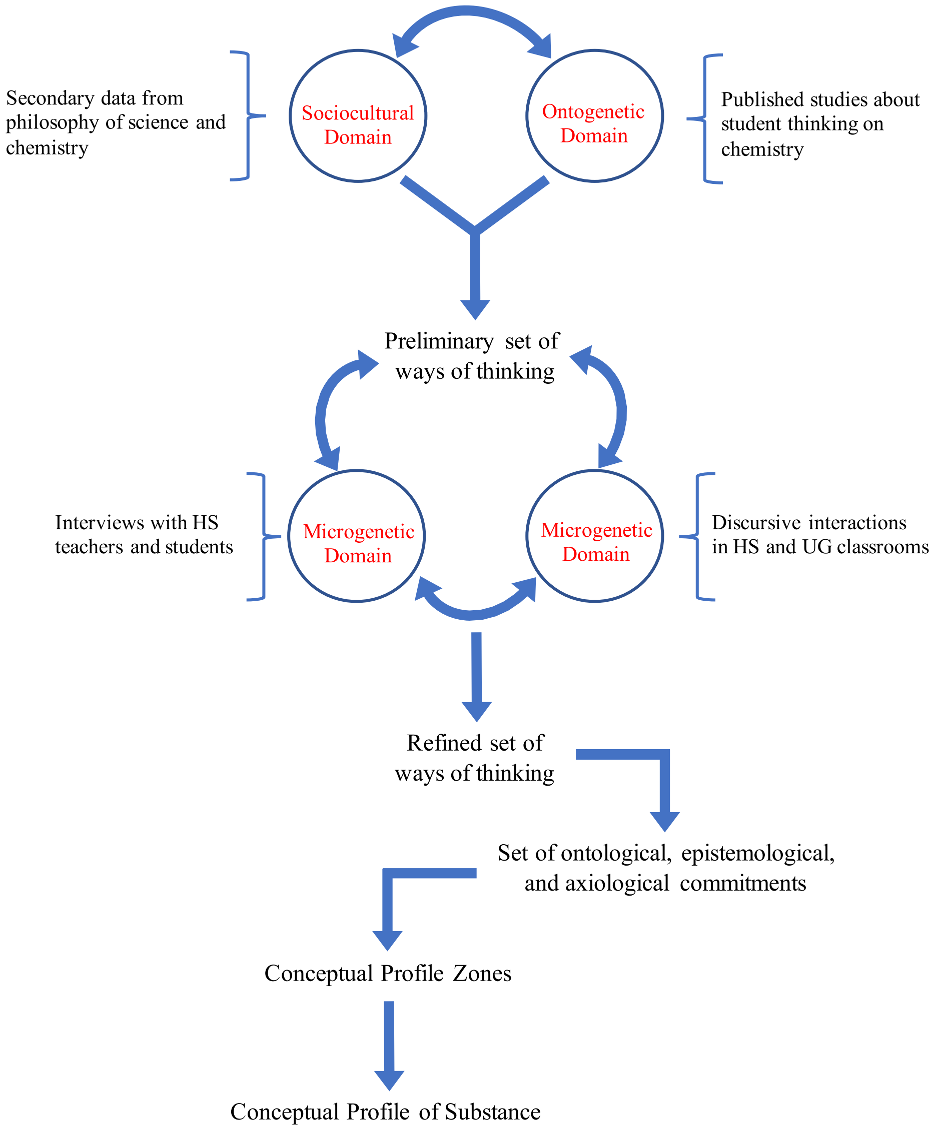

Fig. 1 Flow diagram that illustrates the process of building the conceptual profile of substance

of ontological, epistemological, and axiological commitments that stabilize the conceptual profile zones of substance. Subsequently, the conceptual profile of substance developed during this research study was tested by employing it to analyze and represent high school and university students' and teachers' thinking about substance when engaging in a formative assessment activity.

2.1 Building the Conceptual Profile of Substance

The conceptual profile of substance was built from both secondary and primary data spanning three genetic domains. This section describes the methods employed with the sociocultural and ontogenetic domains that correspond to the upper third of Fig. 1.

2.1.1 Data Collection

The construction of the conceptual profile of substance was made possible by the integration of secondary and primary data sources that resulted in a variety of data. This supported the exploration of three genetic domains: (1) the sociocultural domain through gathering secondary data from the history and philosophy of chemistry related to the evolution and nature of substance; (2) the ontogenetic domain by obtaining published findings of students thinking about substance; (3) the microgenetic domain through producing primary data from video and audio recordings of teacher and student interviews and formative assessments in the chemistry classroom, as well as collecting questionnaires that were completed by the students during this formative assessment. The details of each genetic domain exploration are presented later.

In order to collect data related to the sociocultural and ontogenetic domains, several keywords (such as substance, properties of substance, and composition of substance) were used in an exhaustive search of secondary data related to the concept of substance employing three main online databases (ERIC, Web of Science, and Google Scholar). Titles, abstracts, and introductions of an initial set of 197 papers from a variety of publication dates, methodology utilized, and country of origin were read to determine whether they were useful sources of data. Regarding the secondary data from the ontogenetic domain, published studies which involved participants from different academic levels, gender, age, and cultural background were part of the sources. The criteria for identifying and selecting were (1) the secondary data appeared to be based on presenting and analyzing thoughts about substance and would support answering the research questions; and (2) secondary data stemmed from studies that had well-grounded study purposes, justification of methodology and instrument(s) employed, as well as description of sampling (who were the participants, as well as when and where the data were collected), and identification of any known biases. Under these criteria, 83 papers from the sociocultural domain and 74 papers from the ontogenetic domain were selected to be part of the exploration of the polysemy of substance. It is important to mention that most of the published studies from the sociocultural domain were related to the Occidental history of chemistry and contemporary Western philosophers' debates about the concept of substance. Regarding the secondary data from the ontogenetic domain, several of the published studies were based on learning progressions research in the USA. We considered this work relevant because students' ideas from a range of educational levels were explored. In addition, the vocabulary employed by the original authors of these published studies was used when studies were analyzed as part of examining the sociocultural and ontogenetic domains. In the original context of those studies, terms such as "naïve" and "folk" refer to ideas of students who are considered to be novices in the novice–expert dichotomy under which that research was carried out. Although those studies were carried out from a different perspective than the present study, the findings of the prior studies still hold relevance because other ways of thinking than the canonical model-based science views are often expressed.

The microgenetic domain was explored by collecting primary data from eight chemistry teachers and their students, which included four high school teachers involved in a more detailed analysis (Bruno, Red5, Rogue1, and PurpleTree), four other high school teachers (Kitty, Sophocles, TacoTaxi, and Thomas), and one university chemistry teacher (Mariam). All participants, teachers and students, belonged to public schools in the Northeastern US. These schools are characterized by having a wide range of teachers' and students' cultural backgrounds such as ethnicity, academic level, socioeconomic status, country of origin, and native language. Diversity among the schools was valued for its ability to include the influences of many cultural backgrounds regarding ways of speaking and thinking about substance. Eight of the chemistry teachers (all but Kitty) were asked to implement a formative assessment activity called Thinking-through Cards (T-tC) in their classrooms, to video and audio record the entire formative assessment implementation (opening, developing, and closing of the activity) wearing a body camera and placing a voice recorder at each table where consented students were seated, and to collect students' written responses after they engaged in the T-tC activity. Before describing the characteristics of the T-tC activity, it is pertinent to clarify our meaning of formative assessment to understand why the T-tC activity was considered a type of it. Formative assessment uses a "planned for interaction" task which consists of a set of questions that a teacher designs and implements at particular times in a classroom activity (Shavelson et al. 2008). Formative assessment activity allows a teacher to elicit students' ideas, notice and interpret the core of those ideas, and carry out guidance and support students' learning based on those ideas (Dini et al. 2020). For students, a formative assessment activity offers a space to hear their own and classmates' ideas, interpret those ideas, and work collaboratively to solve a specific problem in the classroom. The T-tC activity is seen as a formative assessment activity because on the one hand it allows teachers to elicit students' speech and thoughts about substance to notice and interpret them in order to act to guide and support students' understanding about substance, and on the other hand it allows students to bring their ideas about substance and work on them to better understand what substance is.

The T-tC activity asked students to choose first individually and then collectively the best and worst examples of substance among six items on cards, and then to provide reasons for their choices. The items on the cards were star, dinosaur, smell, heat, light, and T-shirt. In addition, if students thought the items in the cards were not good examples of substance, they were asked to add two items to the set of the cards and explain why these new items were better examples to illustrate substance. The main intentions of the design of the T-tC activity were to make it both accessible for all students and revealing of students' ways of thinking about substance. To avoid pushing students to merely provide scholarly definitions, prototype examples of substance (such as NaCl, H_2O, and O_2) were not used. The items on the cards came from analyzing pilot data of a questionnaire regarding the concept of substance, ideas of possible effective items to be interpreted in many ways (for instance, dinosaur and star), and influences from previous instruments in conceptual profile theory (Mortimer and El-Hani 2014). Thus, these items were considered relevant for students based on experiences many students have had, the likelihood of generating different interpretations, and not being prototype examples. Instead of including a representation of each item on the cards, it was decided to include only the written words because the intention was not to lead the students to a particular depiction of the items. This allowed students to imagine the items based on their own perceptions and choices. For instance, when thinking about dinosaur, students brought different interpretations, such as a dinosaur being a living organism or dinosaur fossils. This generated considerable discussion about whether a substance needed to exist or not. With a representation of a dinosaur, students could have been moved toward thinking about dinosaur as a living organism. Lastly, we refer to star, dinosaur, smell, heat, light, and T-shirt in the T-tC activity as "items" because item is a neutral term. We found in pilot tests that calling these "words" had the effect of leading students to think about dictionary definitions.

The microgenetic domain was also explored with 2 chemistry teachers, Kitty and Thomas, and 21 high school students from diverse, urban, public schools in the Northeastern US. None of the student interviews were with participants who had participated in the T-tC activity, and one of the teachers (Kitty) also did not use the T-tC activity with his students. These 23 individuals participated in individual interviews (~25 min) with the first author, in which they were asked several questions such as: What is the first thought that comes to your mind when I say the word substance? Do you consider that one single molecule of water is a substance? How do you know that something in front of you is a substance?

2.1.2 Data Analysis and the Example of the Construction of the Sensorialist Conceptual Profile Zone

The analysis of data was based on one of the two approaches recommended by Mortimer and El-Hani (2014) which is grounded in a dialogical approach; i.e., data from each domain are continuously articulated with the data from other domains. The strategy of analyzing the data from the three different genetic domains started with the interpretation of the sociocultural domain (secondary data obtained from historical and philosophical papers about the concept of substance) and the ontogenetic domain (students' thinking and alternative conceptions regarding the concept of substance). The first approximation of inferring the zones came from the sociocultural domain, and initial ontological, epistemological, and axiological commitments were extracted by partial inductive analysis. The reason for partial inductive analysis with the sociocultural domain was that, once the ontogenetic domain was analyzed, there was a mutual influence to modify the initial zones found in the first approximation and new zones were inferred from the dialog between the historical–philosophical and the students' thinking resources of secondary data about the concept of substance.

The starting point to identify preliminary ontological, epistemological, and axiological commitments was to collect and document ideas and definitions about substance from the sociocultural and ontogenetic domain. Those ideas and definitions about substance were grouped into themes from which one could conceive substance. To identify ontological, epistemological, and axiological commitments, the set of ideas and definitions from each theme was analyzed through posing three general questions:

1. *The ontological question:* What kind of entities/processes does an individual commit to believe exist to make sense about what substance is?
2. *The epistemological question:* What is the basis on which a person justifies her belief that particular entities/processes exist to make sense about what substance is? and
3. *The axiological question:* What evaluative–affective judgments does an individual make to construct her/his relationships with entities/process to make sense about what substance is?

From this analysis, the preliminary zones of the conceptual profile of substance were established. Each of these questions is grounded in relevant theoretical constructs. The ontological question is influenced by the ontological categories proposed by Chi et al. (1994). The epistemological question shares features of a conceptual ecology outlined by Park (2007). According to Mattos (2014), the axiological question relies upon the role of emotions in the regulation of individuals' higher psychological functions. In common with what Gupta et al. (2010) proposed about flexible ontologies, the present study conceives ontological, epistemological, and axiological commitments as flexible, dynamic, and context dependent.

The preliminary zones identified from the theoretical data functioned as a coding framework to analyze ways of speaking from the microgenetic domain. The data from teacher–student and student–student discursive interactions from the T-tC activity, the questionnaires from the eight chemistry classrooms that participated in the formative assessment activity, and the teacher and student interviews from Kitty's and Thomas's classrooms were exhaustively analyzed with the preliminary conceptual profile zones in order to refine the ontological, epistemological, and axiological commitments of the preliminary zones, and to identify ways of speaking that functioned as enunciative characterization for each zone in the conceptual profile of substance. To ensure trustworthiness of the analysis, the authors of the present paper and six non-author members of their research team analyzed approximately 70% of all transcripts to obtain consensus on coding. Once saturation was reached (i.e., all the zones that were identified from the sociocultural and ontogenetic domain were found and extended from the episodes of discursive interaction and questionnaires), the data from the interviews were used to reach internal consensus on the constructs (Evans 2013). Next, we describe how the analysis of data from different domains led to the identification of ontological, epistemological, and axiological commitments which stabilize the conceptual profile zones of substance, as well as the ways of speaking that were related to the conceptual profile zones. The construction of the sensorialist conceptual profile zone is used to illustrate the dialogical analysis of the data.

2.1.3 Example of the Construction of the Sensorialist Conceptual Profile Zone

In the sociocultural domain, patterns were found in several resources of secondary data about the concept of substance (Broackes 2006; Earley 2009; Hacker 2004; Nordman 2006; Paneth 1962a, b; Partington 1948). The secondary data that are shown are not all the papers that were analyzed, but the ones that were most useful to illustrate where the patterns emerge. Paneth (1962a, b) states that chemistry has an origin as a science discipline from the naïve-realistic worldview; indeed, he explains that chemistry has retained a considerable naïve-realistic residue. Actually, based on Aristotle's ideas, substance is considered a concrete object because all substances can be discussed in terms of their species, genus, and many other characteristics (properties) (Earley 2009). Ayers (1999) claims that the sense of materiality of substance can be evidenced through classifying the category of substance into "things, such as dogs or oak trees, and homogeneous substances or stuffs, such as gold or water. This is a division of types of substance corresponding to […] two types of individual: on the one hand, material objects and, on the other, such quantities of stuff as the gold in this ring" (p. 46). Related to these views, substance can be seen as a thing/stuff (Broackes 2006; Hacker 2004). When the ontological question (What kind of entities/processes does an individual commit to believe exist to make sense about what substance is?) is posed to interpret the ideas described earlier, an ontological commitment can be identified. These ideas are ontologically grounded because they situate substance as an entity, particularly as a concrete or material object. Thus, substance seen as a thing/stuff is an ontological commitment to make sense about what substance is.

This ontological commitment related to seeing substance as a thing/stuff was also found in the ontogenetic domain (Au 1994; Dickinson 1987; Krnel et al. 1998, 2005; Liu and Lesniak 2006; Ngai et al. 2014; Smith et al. 1985; Solomonidou and Stavridou 2000; Vogelezang 1987; Wiser and Smith 2008). According to Solomonidou and Stavridou (2000), students' initial ideas about substance are based on conceiving concrete substances such as what students know from their daily lives. Ngai et al. (2014) state that there is a trend in novice students' thinking about substance related to "objectivization" of materials, due to there not being a clear differentiation between object and material.

On the other hand, patterns emerge from the sociocultural and ontogenetic domain associated with the epistemological commitments. Bachelard (1973) states that the first approximation that an individual does to conceptualize what an object is relies on her senses, i.e., her first impression. Bachelard calls this intuitive realism. Aristotle calls these substance's characteristics, which can be identified through the senses, as accidental and essential properties (Broackes 2006). In order to distinguish between the accidental and essential properties, Hacker (2004, p. 44) provides an example:

> *With respect to any substance, we can typically distinguish between properties that are essential for the thing to be the kind of thing it is and properties that are inessential (the accidents), even though we may be forced to recognize a degree of indeterminacy in the essential properties and hence borderline cases of being a such-and-such. An individual diamond must consist of carbon in appropriate crystalline structure, and must have a scratch hardness of 10 on the Mohs scale—these are essential properties. But it may be large or small; white, blue, red, green or black; be set in a crown or other setting—these are accidental properties.*

Eventually, Aristotle expanded his way of conceiving substance and referred to it as a concrete individual which its properties can be "predicated" (Broackes 2006).

From the ontogenetic domain, Ngai et al. (2014) found that the initial way beginning learners have to figure out the identity of a substance, or how to differentiate one substance from another, is through surface similarities (color, shape, size, etc.). Also, Au (1994) states: "given how counter-intuitive the particulate theory of matter is, young children are unlikely to conceive of matter as particulate. For children, a more plausible—although incorrect—conception may be that substances are homogeneous and continuous. Children could use this core belief about substances to trace substance-kind identity and generalize substance-relevant properties (color, taste, smell, etc.) across different portions of stuff." (p. 123). According to this, novice students' ideas about substance tend to rely on seeing substance as *everything that surrounds us*, as their only criterion to describe a substance is through its size, familiarity, and form (e.g., whether it is powder, liquid, etc.) (Dickinson 1987). While the aforementioned ideas are based on the ontological commitment of seeing substance as a thing/stuff, they offer insights about strategies that individuals follow to know that a substance (i.e., a thing/stuff) exists. If the epistemological question is posed to analyze the ideas from the sociocultural and ontogenetic domains presented earlier, an epistemological commitment can be identified. The epistemological commitment associated with the ontology "a substance is a thing/stuff" is: *a substance is a thing/stuff because an individual can observe it using senses*. The definition of substance comes through the senses; what substance is consists exclusively of observational reports and statements derivable from senses.

From the identification of seeing substance as a thing/stuff (ontological commitment) and observing substance by using senses to prove its existence (epistemological commitment) in the sociocultural and ontogenetic domain, it was possible to establish the basis for a preliminary conceptual profile zone, the sensorialist zone. This preliminary zone was articulated with the data concerning the microgenetic domain. As an example, the sensorialist zone also emerged in student discussions in Bruno's classroom (Bruno is the code name of one of the eight chemistry teachers who implemented the T-tC formative assessment). Keila and Love (code names of chemistry student participants), who engaged in discussion with others at their table and with their teacher, illustrate a very common example of this from the data:

01 ***Keila:*** Substance is like, it's something you can see and touch.
02 ***Bruno:*** Something you can see and touch? I do not know. What do you think?
03 ***Keila:*** I think that substance is like something you can touch and see.
04 ***Bruno:*** Okay. Does everybody agree with that?
05 ***Love:*** Yeah. It could be the T-shirt.

From this short conversation that Keila and Love had with Bruno, it can be interpreted that Keila and Love were ontologically committed to the idea that substance is a thing/stuff because they started defining substance as "it's something […]." Based on their decision of considering T-shirt the best example of substance, it is likely that their choice was made based on noticing that the only thing/stuff among the items on the cards (Smell, Dinosaur, Light, T-shirt, Star, and Heat) was T-shirt. On the other hand, Keila said that "it's [substance's] something you can see and touch." This way of speaking revealed the epistemological commitment of Keila and Love because it was through the use of senses (seeing and touching) to justify that "something" (a thing/stuff) exists to make sense about what substance is.

Consider the following two emergent ways of speaking that led to the extension of the sensorialist conceptual profile zone, both of which were spoken by a student with code name A in the classroom of Kitty (one of the eight high school teachers). In the first quote, A was talking with her classmate about defining substance in a "chemistry-like way." The second quote was from an interaction when Kitty stopped by the table and asked the students which item on the cards was the best example of substance.

- *Oh well I guess if you can touch and see something you could measure it because (inaudible) like—like because you could measure the mass of the star, you just (inaudible) its particles, what it's made out of I mean it's difficult but I think you can and then a T-shirt you can measure its mass.*
- *We were thinking a lot of like something that's like, I guess like either like it's tangible or you could see and you know it's there and smell is a sense so it's not really a substance to us. But were again having a lot of trouble really defining substance to what it should be.*

The first of these is an example of how the exploration of the microgenetic domain extended the epistemological commitment of the preliminary sensorialist zone that was found from the analysis of the sociocultural and ontogenetic domains. If the epistemological question is posed to analyze A's way of speaking in the first excerpt, it can be interpreted that a manner of knowing what is substance is that A justifies that a substance (a thing/stuff) exists is through measuring its mass using a balance. Thus, a substance is a thing/stuff not only because she can observe it using her senses but also because instruments allow her to measure its properties. Considering the two examples together, the two ways of speaking of A are examples of students' ways of speaking that lead toward the identification of axiological commitments of the sensorialist zone from the microgenetic domain. The axiological question was applied to identify the axiological commitment that stabilize A's sensorialist ways of speaking and thinking. A's two ways of speaking show evaluative judgments that an individual can construct about substance (a thing/stuff that can be seen and touch) based on qualifiers that are tangible and measurable.

Considering the ontological, epistemological, and axiological commitments that were found across all of the data in the sociocultural, ontogenetic, and microgenetic domains, the sensorialist conceptual profile zone is based on the way of thinking that substances are seen as distinct classes of stuff with different perceivable properties (shape, color, texture, mass, smell, volume, taste, etc.) which are identified by the senses or through instruments. A possible (and common) way of speaking related to the sensorialist conceptual profile zone is substance is something tangible that you can see and touch.

2.2 Representing Heterogeneity of Thinking in Chemistry Classrooms

To illustrate the applicability of the conceptual profile of substance, the conceptual profile zones of substance were used to further analyze students' ways of speaking and thinking about that concept in chemistry classrooms. This section describes how a subset of the chemistry classrooms that participated in the T-tC activity were analyzed to represent the heterogeneity of thinking in chemistry classrooms. This section describes the methods corresponding to the microgenetic domain in the middle third of Fig. 1.

2.2.1 Description of Data

From the eight classrooms that participated in video and audio recording of the T-tC activity for the construction of the conceptual profile of substance, a subset of four chemistry classrooms (those of Bruno, Red5, Rogue1, and PurpleTree) was selected to be re-studied in much greater depth with the final version of the conceptual profile of substance. From the video and audio data collected in the 4 classrooms, 4–6 episodes per group across 6 student groups (~96 episodes in total) were selected for analysis based on the relative richness of interactions among participants that generated several ways of speaking and thinking about substance. These episodes were transcribed verbatim by recording what students and teachers said; field notes and observations were not incorporated. Regarding the analysis of the episodes, the transcripts were analyzed as a whole, and then specific parts were selected based on the students' answers that were related to what substance is. In this way, the unit of analysis of these episodes was students' answers to the questions asked in the T-tC activity. In some cases, students' answers were more than one sentence, and they contain more than one way of thinking about substance (i.e., several zones coexist in the same answer).

2.2.2 Data Analysis

The analysis of the episodes from the T-tC activity in the four chemistry classrooms focused on determining the conceptual profile of each classroom (collective conceptual profiles). Several ways of speaking were analyzed through the conceptual profile of substance in order to determine what ways of thinking were present in each classroom. To reach consistency of constructs, the authors of the present paper and 10 members of their research team analyzed the same transcripts to obtain consensus on coding. A spreadsheet was generated to estimate the relative frequencies in which the zones of the conceptual profile of substance emerged from students' and teachers' speeches in each classroom and in the four additional classrooms. Different graphs, which we call *static maps*, were generated from the qualitative analysis of the collective conceptual profiles in order to facilitate the representation of the heterogeneity of thinking about substance in these chemistry classrooms.

3 A Proposal for the Conceptual Profile of Substance

Following the analysis of data from the three genetic domains, which occurred in multiple iterations between the upper and middle thirds of Fig. 1, six zones became stabilized by ontological, epistemological, and axiological commitments. These are presented as a proposal for the conceptual profile of substance. The sensorialist zone was already described earlier as an example of the methods employed in the present study, so we continue with the essentialist zone. The zones are organized in an order that roughly corresponds to their genesis according to the traversal of modern primary, secondary, and tertiary education. For this reason, there is also some correspondence to going from zones which refer more heavily to everyday ways of thinking toward zones that refer more to scientific ways of thinking usually learnt in school.

3.1 Essentialist Zone

3.1.1 Sociocultural Domain of the Essentialist Zone

Essentialism has been a controversial philosophical theory to understand reality since ancient times (Broackes 2006; Hacker 2004; Shand 2003; Witt 1989). According to Witt (1989), an essentialist commitment is that there is an inner core that constitutes and gives properties to objects and cannot change so long as that object exists. The main supporter of this idea was Aristotle who described substance as the primary cause of being, the nature of an entity, and not an element, but a principle (Ferrater-Mora 1965). Based on one of the most important works of Aristotle, Aristotle's Metaphysics Z, substance is the structure from the integration of *matter* and *form*, where *matter* causes any entity to be unique from other entities, and form gives its determination, shape, definition, and intelligibility. Later on, Aristotle started considering *form* as the *primary substance*, the essence of entities, and claiming that *primary substance* (what makes gold to be gold) is the basic entity that persists through change. To clarify what *primary substance* is, Broackes and Hacker (2004) pointed out that "One may destroy the thing and its parts without destroying the stuff (substance) of which it is made, but one cannot destroy the stuff (substance) of which a thing is made without destroying the thing itself" (p. 50).

3.1.2 Ontogenetic Domain of the Essentialist Zone

Essentialism has the connotation of an intuitive belief (Gelman 2003; Ngai et al. 2014; Talanquer 2006). Gelman (2003) proposed that one of the three main characteristics of this "folk" belief is that people consider that there is an unobservable property, an essence, that causes things to be what they are. These essences cannot be observed, but they give a thing its identity and therefore similarity with other things that belong to the same category. An instance in chemistry is that students often think that substances have essences which are qualities that do not change as substances shift their shape, size, or state. Talanquer's model of students' common assumptions about the natural world (2006) offers a lens to narrow down the essentialism way of thinking about substance. Novice chemistry learners hold a commitment that objects and materials in the natural world have an underlying property (essence) that defines their identity, and which seems to exist independently of the objects or materials that present the identity. For example, when red vapors are produced from the reaction between copper and nitric acid, the color of these vapors is the essence that some students identify when they claim that copper is still present.

3.1.3 Microgenetic Domain of the Essentialist Zone

Ways of thinking related to conceiving substance as a combination of matter and form that gives an entity its particularity, shape, determination, and intelligibility, as well as substance as something that persists through change were better understood from the ways of speaking of chemistry students and teachers. During the implementation of the T-tC activity in the high school classroom of Red5 (a teacher), students were discussing how they could be sure about which item on the cards was the best example of substance. Specifically, students were wondering what definition or criteria were the most productive to make the best decision. Below is one of the ways of speaking that Bigd (a student) demonstrated in Red5's classroom when speaking with Experiment (another student). Bigd's way of speaking here revealed a way of thinking about substance related to an essentialist view:

95 ***Experiment:*** But how we know we are right?
96 ***Students:*** Yeah
97 ***Bigd:*** Substance is, at least when you are talking about like the substance of like a paragraph or something, it's like the meat of it […]

Bigd's way of speaking is aligned with the view that substance is a primary form, the essence that gives a paragraph its meaning, its intention, its power, what Bigd calls "the meat of it." From this context, the substance of a paragraph can be understood as the integration of concrete words and sentences (matter) and meanings, intentions, and senses (form) which define what a particular paragraph might be about. Bigd applied his essentialist way of thinking by relating to the meaning of substance in a context that is different from chemistry.

A different way of speaking that led to further construction of this zone was found in the interview that the first author conducted with Kitty (a high school teacher). One of the questions that Kitty was asked was a series of three subquestions: (1) Do you think that this distilled water that is contained in this bottle is a substance? Why? (2) Do you think that a drop of this distilled water is a substance? (3) Do you think that a single molecule of water is a substance? The main intention of this series of questions was to elicit what interviewees paid attention to when determining whether a sample of distilled water at different scales (macroscopic, microscopic, and submicroscopic) was a substance or not. When Kitty was asked whether one single molecule of water could be considered a substance or not, Kitty answered that "the forces that it [the single molecule of water] has, the dipole or hydrogen bonding, the ability to hydrogen bond with other particles is exactly the same as any other one. So, if I say, I think it's substance, and I keep on cutting it in half, half, half, til I find the tiniest particle that is still, in this case, water, that has to be still a substance. It's not changed to anything else." Kitty's way of thinking about substance was based on the idea that water possess essences (dipole and hydrogen bonding) which are unchangeable as the collection of water molecules increases in a system.

3.1.4 Commitments of the Essentialist Zone

From posing the ontological question across the three genetic domains, it can be said that the ontological commitment that defines the essentialist zone is the belief that substance is a basic entity or that it possesses a primary quality. To identify what strategies individuals follow to prove that a basic entity or primary quality exists to make sense about what substance is, the epistemological question was applied to analyze the data from the three genetic domains. It was interpreted that a basic entity or primary quality is justified by the epistemological commitment of identifying observable or unobservable essential qualities that are the evidence that an object has, or recognizing that the object is still, the basic entity. The axiological question was employed to interpret the secondary and primary data to identify the axiological commitment that stabilizes the essentialist zone. The axiological commitment is based on the idea of evaluating that something is powerful because it has matter-form (akin to "the substance of a paragraph" as Bigd described it) or evaluating that something is unchangeable because its primary qualities are still present (e.g., the dipole of a water molecule). These ideas are more important than others when deciding that something is still a substance. Thus, the essentialist zone is based on the idea that substance is seen as the basic entity or set of qualities that gives an object its determination, shape, definition, and intelligibility, and these qualities persist through change. Substance is a combination of matter (what something is made of) and form (which determines it to be a substance).

3.2 Functionalist Zone

3.2.1 Sociocultural Domain of the Functionalist Zone

Functionalism (a theory of meaning derived from Wittgenstein's construct of meaning as use) is motivated by the idea that what it is for something to be an entity is to do or to be used to do a certain action (Block 1980). For instance, something is a carburetor when this something is able to mix fuel and air in an internal combustion engine. Therefore, carburetor is a functional concept. In chemistry, a functional concept is substance because substance can be conceived as an entity that possesses powers or functions (Ayers 1999; Broackes and Hacker 2004; Lycan 1981; Schummer 1998). Substance has potentialities which include several active (affecting other things in an indefinite variety of ways) and passive (suffering an indefinite variety of changes itself) powers. Also, substance has a set of functions which makes it useful for or a contributor to the accomplishment of particular purposes of a user or system (Lycan 1981). This set of functions is evaluated based on users' perspectives about what the entity is doing or how it is being used in a variety of contexts. It is precisely this set of functions and powers of substances that is one of the main targets of chemistry, as a technoscience: namely, to change the material world and benefit humankind. However, these uses and powers of substances might harm living beings and their environment (van Brakel 2014). In this regard, properties such as biological or biochemical properties (like LD_{50}, or antibiotic or anesthetic effects), as well as ecological ones (like ozone depletion potential or the greenhouse effect factor) are constantly identified and evaluated to consider the benefits, costs, and risks of using substances in any context (e.g., school, industry, home).

3.2.2 Ontogenetic Domain of the Functionalist Zone

Studies have shown that science and chemistry students make sense about substance as a functional concept (Krnel et al. 2003, 2005; Liu and Lesniak 2006). Krnel et al. (2003) found that children classify different stuff/substances based on what actions are possible to do with them. For instance, liquids are classified by the action of pouring, gases through the action of blowing, and solids by the action of holding. In a similar study, Krnel et al. (2005) identified that young children start knowing or experimenting with objects and substances by acting upon them or using them. One of the examples that the authors provided was that, when interacting with metals, children noticed that metals make a clattering sound when they are dropped. Therefore, the children used verbs to describe the actions and uses they experienced with substances. Liu and Lesniak (2006) found that students of all grades develop the concept of matter by learning to distinguish between objects and matter through acting on the world. For example, students classified substances by their uses and benefits, such as water for drinking, baking soda for baking, and vinegar for making salad dressing.

3.2.3 Microgenetic Domain of the Functionalist Zone

Several ways of speaking that have relationships with understanding substance through its uses and powers were found in our interviews, as well as in the teacher–student and student–student interactions in chemistry classrooms. One of these ways of speaking emerged in the classroom of Rogue1 (a teacher) during the implementation of the T-tC activity. Snake (a student) was talking with Rogue1 about what substance is. The beginning of their conversation was:

01 ***Rogue1:*** Snake, what do you think substance is?
02 ***Snake:*** Um, the substance is probably T-shirt.
03 ***Rogue1:*** You think that the best example is T-shirt?
04 ***Snake:*** Yeah, because—
05 ***Rogue1:*** Why do you say so?
06 ***Snake:*** Because it's like hard to test, or to experiment with all the other stuff, cause this is like a solid, and you can actually do something with it.

To answer why T-shirt is the best example of substance among the items on the cards, Snake shared some of the actions that someone can do with a given substance, such as testing and experimenting. In Snake's point of view, for T-shirt (a solid) to be a substance, a T-shirt must be used to do something. As the transcript continued, Snake classified the items on the cards by thinking about what someone could do with the stuff/substance depending on its state (solid, liquid, or gas).

3.2.4 Commitments of the Functionalist Zone

The ontological question was used to analyze the data from the three genetic domains. The ontological commitment identified from posing this question is that the functionalist zone consists of the uses and abilities that substance has. To identify the epistemological commitment that stabilizes the functionalist way of thinking, the epistemological question was posed across the data from the genetic domains. Its interpretation is that the epistemological commitment of the functionalist zone is based on the idea that the existence of uses and abilities of substance can be justified through utilizing, manipulating, observing actions, being affected or benefited by substance. From analyzing the data with the axiological question, it was interpreted that the axiological commitment that stabilizes the functionalist zone is based on the evaluation of the uses and abilities of substance in particular contexts; for example, in the case of Snake, the qualifier of being testable is a crucial characteristic to have in order to be a substance. Thus, the functionalist zone is described as follows: substance is defined as something that can do or can be used to do a certain action.

3.3 Naturalist/Artificialist Zone

3.3.1 Sociocultural Domain of the Naturalist/Artificialist Zone

The relationship between natural kinds and substance is a controversial idea among philosophers (Earley 2009; van Brakel 2014). Schummer (2003) proposes three notions of nature in chemistry: the static, the teleological, and the dynamic. The *static* notion of nature in chemistry is based on the ancient view that chemical crafts change primary qualities of matter, and therefore these changes seemed to be against the nature of God's creation. Chemical crafts were disapproved in the Christian tradition on the basis that there was a set of entities and processes whose essential properties should be preserved. Eventually when alchemy arose, the alchemical art was seen as an art that imitated nature. One of the most famous practices of alchemists was the attempt to make gold by producing either perfect or imperfect replicas. According to Schummer, this notion of nature corresponds to the *teleological* one. When the alchemical art focused its attention on the preparation of medicines in Paracelsian iatrochemistry,[1] the *dynamic* notion of nature started emerging. This notion is grounded in the paradigm that chemical manipulations of matter are not intended to be against the forces or laws in nature. All chemical transformations are seen as natural processes whether they produce known or new substances, and whether they follow established pathways or novel ones. Therefore, every substance obtained from chemical transformations is a natural one because it is the product of a natural process. The dynamic notion of nature in chemistry was stable until the contemporary times (early 1970s) when public attitudes toward environmental pollution and health concerns, due to toxic substances, began to grow. Chemists were blamed as the main people responsible for these emerging threats to nature. Subsequently, the static notion of nature reemerged in society, and nowadays it is common for people to classify substances as natural or artificial (where artificial means substances that are against nature).

3.3.2 Ontogenetic Domain of the Naturalist/Artificialist Zone

Turning to literature on student thinking, knowing the "history" of a sample can influence the way students determine its identity (Johnson 2000; Ngai et al. 2014; Ngai and Sevian 2017). When determining the identity of a substance, students often consider where the substance

[1] Chemical medicine: ἰατρός (iatro) was the Greek word for physician or medicine, and iatrochemistry was a school of thought in the sixteenth and seventeenth centuries with the goal of understanding medicine in terms of chemistry.

comes from and what process has been applied to the substance (Johnson 2000). Students also reason that a given substance is different if it comes from two different sources; for example, natural versus synthetic samples of the same substance are thought to be different (Ngai and Sevian 2017; Rozin 2005). Related to this way of thinking, when judging substances according to their sources, Banks et al. (2015) found that, when asked to choose the best fuel for an amusement park GoKart, a large fraction of students reasoned that fuel was "good" if the combustible was natural and abundant, and "bad" if the fuel was manufactured.

3.3.3 Microgenetic Domain of the Naturalist/Artificialist Zone

This prevalent natural versus artificial way of thinking about substance was also evident in the microgenetic domain. For example, when Pink (a high school student) was asked to say what her first thought is when she hears the word substance, she answered "I think of chemistry; I think part of that's cause I'm taking chemistry this year, but I think of like the idea of like things that are being created and things that are here, like that are tangible, most often, is mostly what I think of." The dichotomy between *things that are being created* and *things that are here* is the basis of Pink's answer. Immediately after she said this, Pink was asked what she meant when saying "things that are created." She replied, "I think sometimes it depends on the substance; like some are manmade, and for various different reasons, like to create a certain compound that would make a certain medicine, or sometimes they're made naturally and in Earth, in the atmosphere, and some are made both ways, like water can be made naturally or it can be created from like humans in a lab." Pink's elaboration confirms that she was thinking about the difference between man-made and naturally occurring substances, which is related to what chemistry is about for her. This dichotomy was also observed when Pink was asked to explain a representation (Fig. 2) that she drew to illustrate substance. She explained, "But based on my definition, it was really hard to come up with like one physical like representation, since like there's so much like that is a substance out there; so, I started with drawing Earth, because Earth is just made out of substances, and substances are around everywhere, and then I thought about how Earth isn't really the only place that substances are found."

The dichotomy between natural and artificial also emerged from the implementation of the T-tC activity in Bruno's high school chemistry classroom. When the students and Bruno were engaged in a whole-class discussion about how each group reached a consensus and what the best example of substance was for them, Dopeboy (a student) said, "I think substance is a natural matter." After Dopeboy's contribution, Bruno asked students to keep that substance definition in mind and then to think about an example of "a natural form of matter" that they had studied before. A student mentioned gold and Bruno approved and wrote this on the whiteboard as an example of "a natural form of matter." Bruno and the students had a conversation about elements as natural substances for a while, and then Strawberry (another student) asked the entire group a question:

50 ***Bruno:*** Okay. And are elements natural substances, like Dopeboy mentioned, like a type of matter, natural matter? Okay, Strawberry.

51 ***Strawberry:*** But is not it, like we cannot create a substance. Like is not it like, can a scientist create a substance?

52 ***Bruno:*** Good question.

53 ***Strawberry:*** Is it always have to be natural?

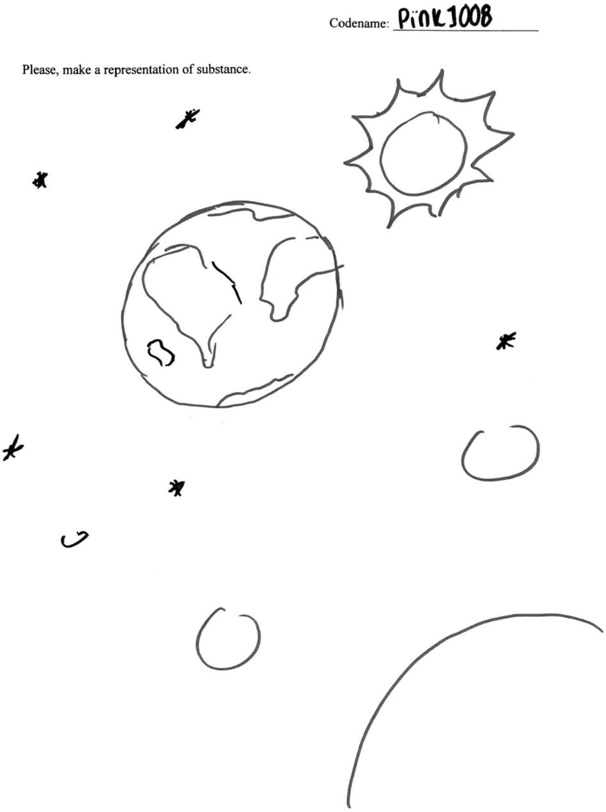

Fig. 2 Pink's representation of substance based on the source where they can be found

54 ***Bruno:*** Good question. I never said that the natural thing was correct. I just had an idea that it would get us to think about elements. Okay? So let us look at another example. So we have elements. What can elements make?
55 ***Strawberry:*** Chemical reactions.
56 ***Bruno:*** Think about copper cycle. In the copper cycle experiment, we started with an element, copper, and we ended with copper. But in between all of the steps, what did we have?
55 ***Students:*** Compounds.
56 ***Bruno:*** Compounds. Okay. Do you think a compound could be a substance?
57 ***Students:*** Yeah.

Strawberry was seeking an explanation for why the interplay between natural and synthetic substances had not been established in the classroom. However, Bruno saw chemical reactions, specifically the copper cycle, as an entry point to start talking about the transformation of elements to obtain other types of substances, compounds. Even though Bruno and her students did not make explicit the two different sources (natural vs. artificial), they implicitly negotiated that elements are substances that are naturally occurring, and compounds are substances produced by chemical transformations of elements.

3.3.4 Commitments of the Naturalist/Artificialist Zone

To identify the ontological commitment that is related to the naturalist/artificialist zone, the ontological question was posed across the data from the sociocultural, ontogenetic, and microgenetic domains. The ontological commitment that stabilizes this zone is based on the idea that different sources exist from which substances can be obtained. The epistemological commitment, which was identified through posing the epistemological question across the data from the three genetic domains, that also stabilizes this way of thinking is that the existence of these sources that substances can be obtained from are justified by the practices of discovering and encountering substances in nature, and making, producing, and transforming substances in laboratories and industry. From employing the axiological question to analyze the data across the genetic domains, we identified that the axiological commitment of this zone is based on adjectives that express the evaluation of the sources and practices from which substances can be obtained. For instance, the "good" qualifier can be given for natural sources, but the "bad" adjective for synthetic ones. Thus, the naturalist/artificialist zone is defined as: substance can be either a type of object which occurs naturally in the Earth (it is an entity that has an existence independent of the act of perception and its name) which is discovered by scientists, or something that comes about in chemistry laboratories/industry and is made via particular processes by scientists.

3.4 Compositionist Zone

3.4.1 Sociocultural Domain of the Compositionist Zone

The relation between the conceptual structures about things and those that focus on the matter of which they are made is an active philosophical interest (Chalmers 2008; Chang 2011; Hacker 1979; Shand 2003). Philosophy of science has alternatively treated substances as material entities that are the stuff of which objects consist (Hacker 1979). Substances have been also recognized by being made *of*, that is, constituted of some stuff or kinds of substances. In this regard, Chang (2011) proposed the compositionist way of thinking as one of the most common schools of thought that have guided the practice of chemistry. At the times when principlism was a predominant paradigm in chemistry, compositionism relied on the ontological assumption of immutable basic substances; i.e., basic substances that kept their actual identity in the substance they made up and would be separated from each other without any change in their nature. Later on, in the history of chemistry, the practice of this discipline was based on performing chemical analysis (decomposing substances into their constituent parts) and syntheses (producing substances from their primary constituents) which led to the way of thinking of understanding chemical transformations as separation or re-grouping of basic substances into substances. Chang calls these chemistry ways of doing and thinking "Lego Chemistry." When Lavoisier started measuring weights to better understand the practices of decomposition and re-composition, he proposed a new compositionist way of thinking centralized in the notion of indestructible chemical basic substances (elements). However, the compositionist way of thinking was not based on an atomist paradigm yet. What Chang calls the atomization of compositionism emerged from the integration of the work of Lavoisier, Richter, and Proust on measuring the weights of substances in chemical transformations that led to the identification of fixed proportions of weights when substances were combined, and Dalton's rationalization about considering the combining weights into atomic weights through proposing that chemical reactions were atomic combinations in simple ratios of atoms. Therefore, chemical atoms started being seen as the substance's smallest constituents that are all alike, and the fundamental units of chemical reactions (Bernal and Daza 2010; Chalmers 2008).

3.4.2 Ontogenetic Domain of the Compositionist Zone

From interacting with objects in everyday life, both adults and children start conceptualizing substance through learning the names of common materials (wood, metal, plastic, paperboard), and then by finding out that these materials are what some objects are made of (Dickinson 1987). Once people begin learning science and chemistry in schools, the ways they relate substance with composition are complexly diversified. For instance, Renström et al. (1990) explored students' (13 to 16 years old) conceptions of matter and found seven different ways of thinking. Four of them were directly related with their views about substance: (1) small particles may be different from the substance in which they are embedded; (2) substance consists of infinitely divisible particles which might not consist of the substance; (3) substance consists of particles that are not divisible into other particles and have certain attributes (such as form and structure) that may explain macroproperties of the substance; (4) substance consists of systems of particles. Different macroproperties of the substance can be accounted for in terms of properties of particles and a particle system (p. 566). These ways of thinking about the relation between substance and composition rely on seeing substance as a static object constituted by combinations of small particles (atoms, ions, molecules, etc.) with fixed structures and properties.

3.4.3 Microgenetic Domain of the Compositionist Zone

Analysis of the data from the T-tC activity implementation and the student and teacher interviews led to the finding that both students and teachers exhibit ways of thinking about substance that rely on a relation between substance and composition. When asked to represent substance, Tsuna (a high school student) drew a "Lego" structure (Fig. 3). The student described her representation as, "From what I've said anything that can mix something into, anything that can be made of something I say is a substance. So, I thought on like Legos, or even building blocks where if you put them together you will build something new." From

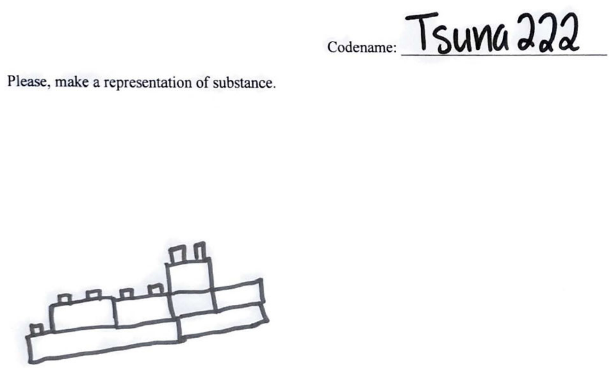

Fig. 3 Tsuna's representation of substance as a building block of stuff

Tsuna's way of speaking, it can be said that substance was perceived as the *furniture of reality* (Hacker 1979) because substances are the components of objects; the building blocks that are put together to construct something new.

Another example emerged from Messi's way of speaking when he was describing his representation of substance (Fig. 4). Messi said "[substance is] the foundation of chemistry; the basics of a reaction, or something of that sort where you're putting one substance with another and in chemistry you are expecting like a reaction or something like doesn't react". Messi was then asked to provide an example to better illustrate this idea, and he mentioned the reaction between sodium and water where both *the metal* and *the liquid* were substances. Messi's way of thinking about substance relied on the idea that substances are made of other substances through chemical combinations (addition of basic substances to synthesize something new).

When Icky (another student) was asked the same question about representing what substance is for her, she drew a sub-microscopic representation of water (Fig. 5). She described her drawing as, "I drew a glass of water with its smallest units. So I drew a water molecule which is made of two oxygen atoms and one hydrogen atom, and that makes water. So in this water there are millions of them, but they're really, really small to see, and so many of them will make up this glass of water." Icky's representation and description were aligned with the idea that substance is made up a collection of least particles which are all alike. Also, Icky went deeper in her explanation and described the composition of the water molecules.

3.4.4 Commitments of the Compositionist Zone

The use of the ontological question to analyze the data from the three genetic domains led to the identification of the ontological commitment that is characteristic of the compositionist zone: substance is units (particle, atom, molecule, etc.) because substance is seen as either made of other substances or as a collection of least particles that are all alike. However, these components (substances/particles) are seen as static systems with fixed properties. Through asking the epistemological question, the epistemological commitment that stabilizes the compositionist way of thinking was identified, and is based on the practices of decomposing and synthesizing substances, as well as knowing and naming the materials that compose

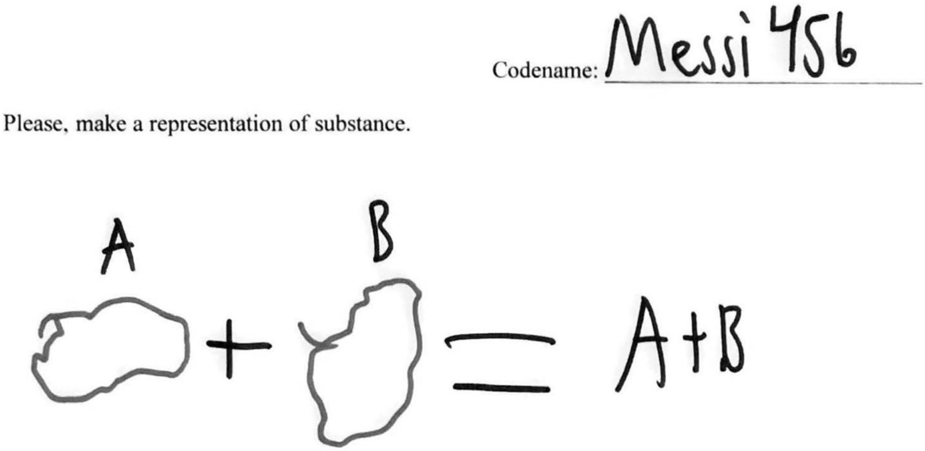

Fig. 4 Messi's representation of substance as made of other substances through chemical combinations

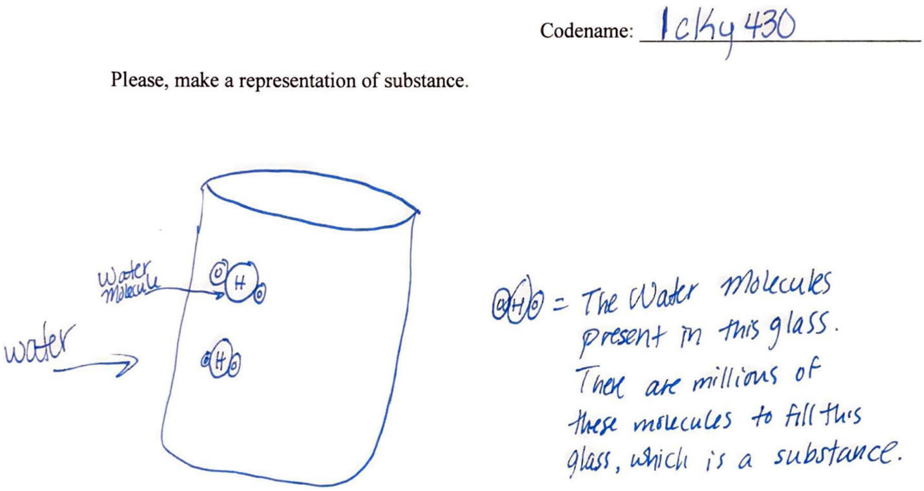

Fig. 5 Icky's representation of substance as made of a collection of smallest particles that are all alike

substances. To identify the axiological commitment that characterizes this zone, the axiological question was employed to analyze the secondary and empirical data. It was identified that the axiological commitment relies on the evaluative judgments that a person can make regarding the kinds of components that constitute either an object or a substance (substance–composition relation), as well as the system in which these are embedded. For instance, a person can think that a spoon made of wood is cheaper than one made of metal when deciding which one to buy, or a person can think that methane is a dangerous gas because a methane molecule has four atoms of hydrogen which makes the gas explosive. Thus, under the compositionist zone, substance is defined as either

- The underlying constituents of everything (building blocks); or
- A system made of materials, elements, compounds, and/or mixtures of compounds/elements; substance is involved in methods of decomposition (applying various methods to take a substance physically apart into its constituent parts) or synthesis (producing a new substance from its progenitor materials); or
- A static system that has small parts (molecules, atoms, ions, particles, etc.) which are all alike and have fixed structures and properties, and can combine in simple and characteristic ways to form the least parts of other substances.

3.5 Interactionist Zone

3.5.1 Sociocultural Domain of the Interactionist Zone

Traditional philosophers of science and chemistry have understood substance as a static entity and considered substance's changes as the secondary focus of their analysis regarding what substance is (Stein 2014; van Brakel 2014). However, contemporary philosophers have proposed *process philosophy* to justify the idea that there are not isolated substances in the natural world, but only constant changes of those substances (Cobb and Griffin 1976; Earley

2013; Stein 2004; Whitehead 1978). Under the process thought, substances are seen as dynamic systems that undergo continuous reversible and irreversible transformations that take place on different timescales. Substance, as a dynamic system, contains many species (molecules, atoms, ions, radicals, etc.) in equilibrium, and these species' presence depends on temperature, pressure, and other contextual variables of the system (van Brakel 2014). According to Stein (2004), substance (as an entity) is just a temporary state which exists as the stable patterns established by sequential processes; those processes are existentially central for the substance. Therefore, the properties of a substance are merely relational and emerge from the interaction of the substance with other substances and/or its environment (Bernal and Daza 2010). Substances are seen as "ecosystems" and their changes as "environmentally responsive becoming" (Stein 2004, p. 15).

3.5.2 Ontogenetic Domain of the Interactionist Zone

The view of substances as dynamic entities (i.e., processes) was also found in several sources in the ontogenetic domain (Chi 2005; Cooper et al. 2015; Ngai et al. 2014; Ngai and Sevian 2017; Talanquer 2008, 2018). Ngai et al. (2014) pointed out the pragmatic value of the interactionism view to explain that stable properties of a given substance emerge from the interactions of its components. For instance, physical properties of a substance (such as density and melting point) are conceived as emergent properties generated from the interactions of huge collections of particles which compose the substance; on the other hand, chemical properties (such as acid-base and redox) are explained by the interactions between subatomic constituents of single particles. Thinking about processes (e.g., movement of particles) instead of concrete objects (e.g., particles) represents a huge challenge for students and teachers in science and chemistry classrooms (Chi 2005). The development of interactionism is constrained by the shift *across* ontological categories (Chi 1992) from entities to processes. Talanquer (2018) points out the need to conceptualize components of substances as having extrinsic properties which emerge from dynamic and probabilistic interactions with different environments and entities. Developing the concept of emergence is not only crucial to deeply grasp the behavior of different substances in chemistry but also systems in physics and biology that manifest self-organization (for instance, enzymatic reactions, evolution of organisms, etc.) (Talanquer 2007).

3.5.3 Microgenetic Domain of the Interactionist Zone

The emphasis of thinking about substance as a dynamic system was found in few instances in the microgenetic domain. When Kitty (a high school teacher in the present study) was asked where the properties of substance come from, his answer was:

46 ***Kitty:*** […] Chemical properties are how it reacts with something else. So that depends on the same idea, but because you cannot figure those out unless you change the substance, how it reacts. So, say, for example, oxygen reacts with hydrogen to make water. So, oxygen is a very reactive gas. So how it reacts with things? It reacts with iron. It reacts with us. It burns. You use it to burn. So, oxygen's very reactive. You take then a gas like neon or argon, and it's not reactive. It's, I cannot, it's very difficult to use it to react with things, to make new things or to make things react. And that has to do with electronic properties, the number of electrons it has, and how it wants to bind, how it wants to bind

> to reduce its energy, thermodynamics. But all properties, whether chemical or physical, have to do with the makeup of the molecule of the atom, the number of electrons it has, number of protons it has, its size, things like that.

Kitty’s way of speaking about substance in this quote is based on conceiving chemical properties as being emergent and extrinsic. Kitty started saying that chemical properties are known from the interaction of a given substance with others; for example, oxygen is known as a reactive gas because it interacts with hydrogen, iron, and the human body. To better explain how chemical properties emerge, Kitty compared oxygen with a couple of noble gases (neon and argon) to better illustrate the idea the characteristic chemical properties of oxygen emerge from the electrons that this atom has, as well as its trend “to bind” when interacting with other atoms. Then, Kitty made a generalization to re-state that physical and chemical properties of a substance come from its structure and interaction of its components and component’s subcomponents.

3.5.4 Commitments of the Interactionist Zone

Based on posing the ontological question to analyze the data across the sociocultural, ontogenetic, and microgenetic domains, it was possible to identify the ontological commitment that stabilizes the interactionist zone, as being grounded in thinking of substance as a dynamic entity (i.e., processes) that has extrinsic and emergent physical and chemical properties. From analyzing the data from the three genetic domains through the epistemological question, the epistemological roots of the interactionist zone were found to be grounded in modeling, synthesizing, and transforming substances because interactions at the macro and particle level are considered to represent continuous processes. For instance, in order to model the diffusion of a gas in another fluid, people can represent random collisions and interactions among all particles in the system. The use of the axiological question to analyze the secondary and empirical data led to the identification of the axiological commitment, which relies on people evaluating the characteristics of these interactions and movements, as well as the processes that occur in a system as fast, slow, favored, not favored, spontaneous, not spontaneous, etc. Thus, in the interactionist zone, substance is seen as a dynamic system with stable physical properties that emerge from interactions of a considerable number of its components (molecules, atoms, ions, particles, etc.), and chemical properties of single particles that emerge from interactions among subatomic components.

3.6 Comparison of the Sets of Commitments that Stabilize the Conceptual Profile Zones of Substance

From the exploration of the sociocultural, ontogenetic, and microgenetic domains, six conceptual profile zones were found. Table 1 summarizes the descriptions of each zone with an example (shown in italics) of a way of speaking that was found in the microgenetic domain and was one of the most common ways of speaking found in relatively short interactions in the chemistry classroom. It is important to reiterate that the conceptual profile zones of substance are not hierarchical in terms of their correctness or inherent power. The only hierarchy that exists is based on their genesis; i.e., some zones emerge later than others due to new forms of activity that generate new types of thinking (Wertsch 1991).

Table 1 Conceptual profile of substance: six different zones are the constituents of this profile

Zone	Description	Commitments
Sensorialist	Substances are seen as distinct classes of stuff with different perceivable properties (shape, color, texture, mass, smell, volume, taste, etc.) which are identified by the senses or through instruments. For example, *substance is something you can see and touch*	– Ontological: stuff, object – Epistemological: seeing, smelling, touching, feeling, measuring – Axiological: tangible, testable, measurable
Essentialist	Substance is seen as the basic entity that gives an object its determination, shape, definition, and intelligibility, and that persist through change. It is a combination of matter (what something is made of) and form (what determines to be a substance). For instance, *if I say, I think it's a substance, and I keep on cutting it in half, half, till I find the tiniest particle that is still, that has to be still a substance*	− Ontological: essential quality (form plus matter), and/or persistence − Epistemological: identification of presence of observable or unobservable essential qualities or basic entity − Axiological: powerful, unchangeable, indivisible
Functionalist	Substance is defined as something that can do or can be used to do a certain action. For example, *substance is something that is able to change its form*	– Ontological: uses and abilities – Epistemological: actions of using, manipulating, observing – Axiological: uses and abilities in contexts, e.g., useful for, able to
Naturalist/artificialist	Substance can be either a type of object which occurs naturally in the Earth (it is an entity that has an existence independent of the act of perception and its name) and is discovered by scientists, or something that comes about in chemistry laboratories/industries and is made under particular process by scientists. For instance, *substance is something that is manmade*	– Ontological: substances obtain from sources – Epistemological: discovering and manufacturing – Axiological: affective evaluation, e.g., natural vs. manmade, good vs. bad
Compositionist	Substance is seen as either: – The underlying "constituents of everything" (building blocks). For instance, *everything is made of substances.* – A system made of material(s), element(s), compound(s), and/or mixture(s) of compounds/elements. Substance is involved in methods of decomposition (applying various methods to take a substance physically apart into its constituent parts) or synthesis (producing a new substance from its progenitor materials). For example, *substance is made of substances/elements.* – A static system that has small parts (molecules, atoms, ions, particles, etc.) that are all alike and which have fixed structures and properties, as well as combine in simple and characteristic ways to form the least parts of other substances. For example, *substance is made of atoms/molecules*	– Ontological: composed of units with fixed structure–property relationships – Epistemological: decomposing, synthesizing, naming, modeling – Axiological: pure, smallest, fundamental, built

Table 1 (continued)

Zone	Description	Commitments
Interactionist	Substance is seen as a dynamic system with stable physical properties that emerge from interactions of considerable number of its components (molecules, atoms, ions, particles, etc.), and chemical properties of single particles that emerge from interactions among subatomic components. For instance, *oxygen's very reactive. You take then a gas like neon or argon, and it's not reactive. […] that has to do with electronic properties, the number of electrons it has, and how it wants to bind, how it wants to bind to reduce its energy, thermodynamics. But all properties, whether chemical or physical, have to do with the makeup of the molecule of the atom, the number of electrons it has, number of protons it has, its size, things like that*	– Ontological: dynamic entity with processes that lead to emergent properties – Epistemological: synthesizing, transforming, modeling – Axiological: likely, faster, spontaneous, predominant

Each conceptual profile zone is stabilized by a set of commitments that are relied upon in ways that are unique to a zone. Two of the zones relate directly to how people interact in daily life with substances. The sensorialist zone is stabilized by the ontological commitment that substance is object/stuff. The existence of these objects and stuff is justified by the senses or by measuring their properties through an instrument. The evaluative–affective judgment that people tend to make is to qualify object/stuff as tangible, testable, measurable, etc. The functionalist zone also refers directly to daily life experiences, but instead of relying on an ontological commitment of object/stuff, this zone refers to uses and abilities. These are justified by the manipulation, or use of substances, as well as the observation of actions that substance can do. There are several qualifiers that people assign to these uses and abilities, including being eatable, useful, and able in other ways.

Two of the zones, naturalist/artificialist and essentialist, refer to the generation of substances, either in their derivation or as their core essence, thus in this sense they are less tangible and more theoretical than the sensorialist and functionalist zones. Regarding the essentialist zone, its ontological category is essential quality and basic entity (matter and form). The proof people rely on for this is identifying the observable or unobservable essential quality or basic entity which usually persists through change. If something has an essential quality or is a basic entity, the axiological commitment tends to be powerful, indivisible, persistent, etc. The ontology that is characteristic for the naturalist/artificialist zone is source. It is through the epistemologies of discovering (in nature) and manufacturing (in industry or chemical laboratories) substances that the existence of different sources is justified. Different qualifiers are given as axiological categories of these sources, including natural, man-made, good, bad, etc.

The remaining two zones, compositionist and interactionist, share two major qualities: they are more explicitly learned in school, and they often are referred to when providing causal mechanistic arguments for ways that substances behave. This may be why both zones include modeling in their epistemological commitments; however, modeling has a different focus and is employed differently in each. Static components such as substances, molecules, and atoms, and fixed structure–property relationships are the ontological category that stabilizes the compositionist zone. These ontologies are justified through the epistemologies of synthesis, decomposition, and modeling. Depending on the kind of component that people consider, an object or substance has several characteristics that are attributed to the constituents, such as smallest, fundamental, and built. In the case of the interactionist zone, the ontological commitment is based on substance as dynamic (process) and emergent structure–property relationships. The existence of this ontology is proven by the epistemologies of synthesizing, transforming, and modeling substances, whose activities involve the consideration of dynamic systems. It is through the consideration of these dynamic substances (processes) that people give qualifiers that include likely, faster, spontaneous, etc., to those processes.

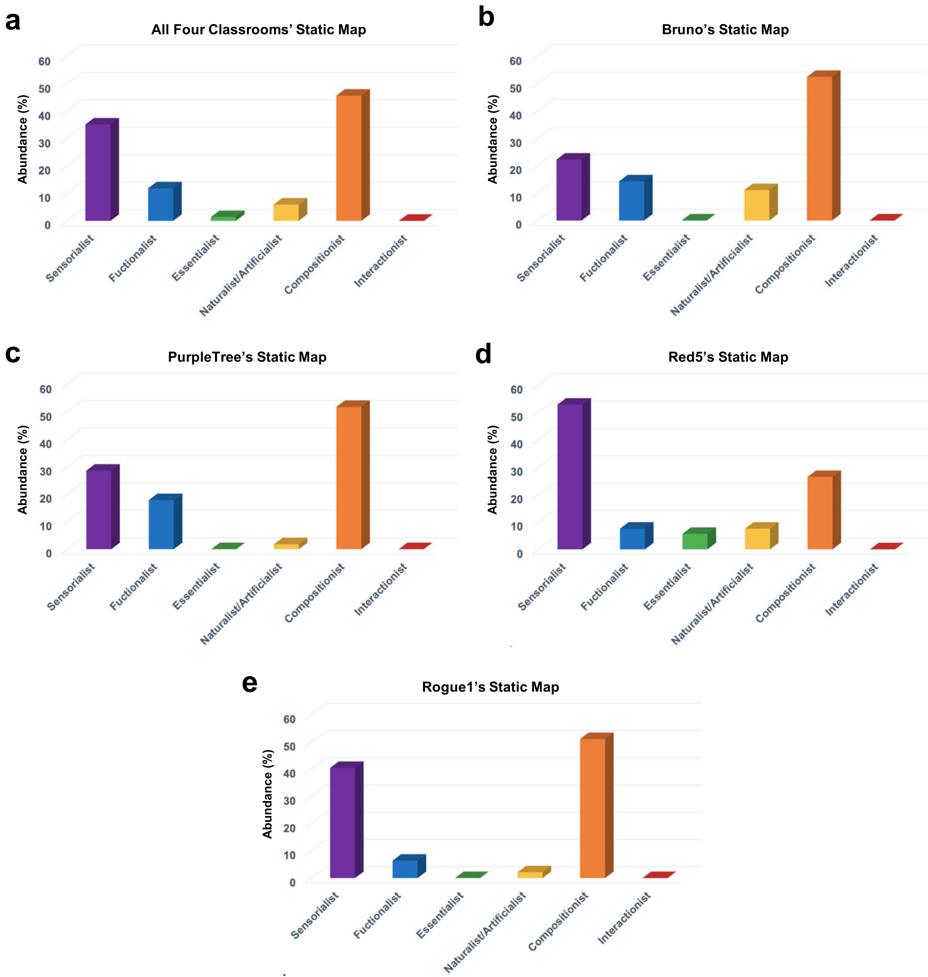

Fig. 6 **a**–**e** Static maps of conceptual profile zones in the four classrooms. The *x*-axis represents the conceptual profile zones of substance, and the *y*-axis the percentage of conceptual profile zones' abundance

3.7 Heterogeneity of Thinking about Substance

To address the second research question, we analyzed more closely the discussions among students and their teachers from four of the classes that participated in the present study. Based on coding all of the ways of speaking by the students in these classes during implementation of the T-tC activity, we found that the compositionist (45.7%) and sensorialist (35.1%) zones were the most prevalent ways of thinking in these four classrooms. The functionalist (11.9%) and naturalist/artificialist (5.9%) zones were used sparsely by students when choosing the best and the worst example of substance among the items on the cards. The essentialist zone (1.4%) was rarely observed in either the students' or teachers' ways of speaking, and the interactionist zone was not present in any of these chemistry classrooms. The static maps shown in Fig. 6 represent the ways of thinking that were present across all four classrooms (6a), i.e., the percentages reported immediately above, and individually in each of the four classrooms (6b to 6e).

A conceptual profile of a community of people depends on the social and cultural context of the group, thus it is to be expected that the profiles of each class (represented by the static maps in Figs. 6b to e) would not be the same as each other. Some insights about differing orientations and sociocultural contexts of the classes may be viewed by considering various demographics and the focuses of the schools. Table 2 summarizes some of these variables, as compiled from the demographics that all schools are required to report uniformly. Schools are required to report the percentages of students whose first language is other than English (which is the language of instruction), of enrolled students who indicate belonging to particular racial/ethnic groups (Hispanic, Black/African American, Asian, and White), and of enrolled students whose family incomes qualify them for receiving free or reduced-price lunch (a federal program). Students who do not speak English as their first language are tested annually to determine English proficiency, and are designated as English language learners and provided support in learning English, depending on the outcomes of these tests. The school focus information was summarized from the school missions as represented on the schools'

Table 2 Demographics and school focuses as a view into sociocultural differences among the chemistry classes

Classroom	School focus	First language not English %	English language learners %	Race/ethnicity* demographics %	Low family income %
Bruno	Recent immigrants with interrupted schooling	100	92.3	Hisp: 48.4 AfrAm: 43.4 As: 4.1	66.1
PurpleTree	Vocational–technical school	35.6	4.5	AfrAm: 40.3 Hisp: 37.5 Wh: 13.2	47.1
Red5	Theater and fine arts academy	52.4	2.6	AfrAm: 33.2 Hisp: 32.5 As: 21.2	46.8
Rogue1	Academically selective school	31.1	0.1	Wh: 45.9 As: 29.1 Hisp: 12.7	16.8

*For race/ethnicity demographics, the largest three groups in each school are listed with the following abbreviations: Hispanic (Hisp), Black or African American (AfrAm), Asian (As), and White (Wh) websites. While all were public high schools, the schools tended to attract students with different backgrounds, language proficiency, career goals, and family income levels.

The most substantial demographic differences between the schools were that Bruno's school had the highest poverty level, the lowest English proficiency level, and almost no White students, while Rogue1's school had the lowest poverty rate, highest English proficiency level, and largest fraction of White students out of the four schools. The focuses of each of the four schools were all distinct, reflecting different interests and/or life experiences of the students, and likely contributed to students having different ways of speaking.

The static map of Bruno's classroom (Fig. 6b) shows that the most predominant way of thinking during the T-tC activity in this classroom was the compositionist (52.4%) zone. It was not only students who shared ways of speaking associated with this way of thinking when talking between each other, but also Bruno, e.g., "an element is a substance because it's made of one type of atom"; and "a compound is a substance because it is made of only one type of either molecule or particle." Other ways of thinking that were relevant for the teacher and some students during T-tC were the sensorialist (22.2%), functionalist (14.3%), and naturalist/artificialist (11.1%) zones, and these three zones had higher prevalence in Bruno's classroom than the classrooms of the other three teachers. The essentialist zone was not associated with any ways of speaking in Bruno's classroom, neither in student–student nor teacher–student interactions. The relatively wider variety of zones in Bruno's classroom, especially when compared with Rogue1's classroom, may be due to Bruno's students bringing a greater variety of life experiences to school, as Bruno's students were recent immigrants from many different continents and countries.

The static map of Rogue1's classroom (Fig. 6e) demonstrates a similar predominance as Bruno's in the compositionist way of thinking (51.0%) when the students were engaged in the T-tC activity. Many students' ways of speaking associated with the compositionist way of thinking, however, originated with Rogue1. For example, when Rogue1 was interacting with a group of students, he asked a group of students "Can you think of a word that might often follow substance or preface substance, like another word or adjective that might go with substance?" His way of speaking was based on the idea of purity (substance is made of only one kind of constituent) as a productive criterion to solve the problem in the T-tC activity. The second most prevalent way of thinking in Rogue1's classroom was the sensorialist zone (40.5%); however, its relative prevalence was much higher than in Bruno's classroom. Contrary to the compositionist zone, students were the main speakers in the sensorialist line of thought in Rogue1's classroom, but often this occurred in a hybrid manner. For example, a way of speaking related to the sensorialist zone was evident when Ilovecats (a student) was explaining why T-shirt was the best example of substance among the items on the cards. She said, "Because it's both physical and can be felt, and a scientist can do experiments around that to reveal its properties." Ilovecats' way of speaking here showed a coexistence of two ways of thinking in her conceptual profile of substance. On one hand, the first part of the sentence ("because it's both physical and can be felt") is associated with the sensorialist zone; and on the other hand, the second part ("a scientist can do experiments around that to reveal its properties") is interpreted as functionalist way of thinking, which was minimally present (6.4%) in Rogue1's classroom. It may be that Rogue1's exclusive use of the compositionist zone led students to perceive that their teacher expected them to rely on a compositionist zone, so they modulated their ways of speaking accordingly. Even less present was the naturalist/artificialist zone (2.1%). The essentialist and interactionist zones did not appear in the students' or teacher's ways of speaking.

PurpleTree and her students (Fig. 6c) mainly talked in terms of the compositionist zone (51.8%). The profile of zones in this classroom was similar to Bruno's except with very little naturalist/artificialist zone. An example of a way of speaking related to the compositionist way of thinking emerged when Annyonghaseo (a student) was asked whether he considered himself a substance or not, he said "Yes. We are made of carbons and other molecules. So are stars. They are made out of like gas." Based on this way of speaking, it can be said that Annyonghaseo was thinking about substance in terms of building blocks which are the constituents of anything in reality. Another conceptual profile zone that was common in PurpleTree's classroom was the sensorialist zone (28.6%), which was exhibited in student speech about substance as a tangible thing, and whether or not a substance was something that necessarily had to be seen. The functionalist way of thinking (17.9%) was relatively frequent during the classroom talk, for example in instances such as "I feel like it's [substance] like things you could measure, basically" (Fishonrice), and "You go to the star and then you take a sample of it, and then you can, and then that's a substance" (Succesfulgod), were identified in the classroom discourse. One characteristic that differed between the sensorialist zone in Bruno's and PurpleTree's classroom was a much greater prevalence of the axiological commitment to testability in PurpleTree's classroom. The naturalist/artificialist zone (1.78%) was not a common way of thinking in PurpleTree's classroom. Similar to Bruno's and Rogue1's classrooms, the essentialist and interactionist zones did not emerge in any speech.

The only chemistry classroom that exhibited the sensorialist (52.8%) zone as the major way of speaking and thinking was Red5's (Fig. 6d). It may be that this line of thinking had greater prevalence in Red5's classroom than the other teachers' classrooms because Red5's students were focused on preparing for careers as artists, so they may have developed more mature ways of thinking using their senses. An example of ways of speaking related to the sensorialist zone is Apricot's definition of substance, which was "something you have to be able to see, and also, like, and if you can see it, it has to be something that you have to be able to touch" (line 24). The presence of the sensorialist zone was such that Apricot and his classmates brought several questions regarding the definition of substance under that line of thought:

80 ***Apricot:*** Is everything on the periodic table a substance?
81 ***Red5:*** That's a wonderful question, actually. I was going to cut off this conversation, but I would love to hear a couple ideas on that. So Apricot asked us, do we think everything on the periodic table is a substance?
82 ***Students:*** Yes.
83 ***Red5:*** You said yes. Why? BB.
84 ***BB*:** Oh, I said yes because I cannot—I do not know why. I do not know why I think it is, but I just, I do not know why. I just know that like it is a substance. Like I just feel like it is.
85 ***Red5:*** You just have some instinct that that's the case?
86 ***BB:*** I cannot define substance. Like I know what a substance is, but I cannot define it. I do not know why.
87 ***Red5:*** Okay, we are going to define it. So I'm glad that you have got it on the tip of your tongue. What's your opinion about the periodic table?
88 ***Soul:*** I do not think that they are all substances.
89 ***Red5:*** Why?
90 ***Soul:*** Cause helium is not a substance.
91 ***Red5:*** Why not?

92 ***Soul:*** Helium is like, it's not, it does not fit the characteristics that we have all been describing. You cannot touch it. You cannot see it.
93 ***Red5:*** You said yes. Why? BB.
94 ***BB*****:** Oh, I said yes because I cannot—I do not know why. I do not know why I think it is, but I just, I do not know why. I just know that like it is a substance. Like I just feel like it is.
95 ***Experiment:*** But how we know we are right?

Functionalist (7.6%), essentialist (5.7%), and naturalist/artificialist (7.5%) zones occurred with similar prevalence in Red5's classroom. Of these, only functionalist tended to coexist in single speeches with compositionist (26.4%), which was the second most prevalent zone. For example, Awesome (a student), when sharing the additional items that he and his group wanted to add to the set of cards, stated "Well, my group and I said water and oil because they involve particles and substance use."

4 Discussion

Substance has been identified as a polysemous concept from the development of its conceptual profile in the present study. Its large variety of meanings and the diverse contexts where substance can be conceptualized have been documented and portrayed in the six conceptual profile zones found through the exploration and dialogical analysis of the sociocultural, ontogenetic, and microgenetic domains. From a balanced analysis of these genetic domains, the ontological, epistemological, and axiological commitments that stabilize each of the six zones of the conceptual profile of substance were effectively identified and clearly represented to better understand the particularities and differences among the zones. Each zone in the conceptual profile of substance generated in the present study is ontologically different from each other; i.e., each zone in the conceptual profile of substance has a unique ontological commitment. However, some epistemological and axiological commitments overlap for some zones. For instance, although the compositionist and interactionist have different ontological commitments (the former is based on static entities and the latter relies on dynamic entities/processes), they share some epistemological commitments, such as modeling. The particular ontology for each zone played an important role when students' ways of thinking were analyzed, because it was through posing the ontological question to interpret students' answers to the T-tC activity that the identification of the zones in the classroom was more informed. However, the epistemological and axiological commitments also support the analysis of students' answers to the T-tC activity to confirm what the ontological commitment said about which zone was used by the students. This careful delimitation of each zone, in terms of the unique set of ontological, epistemological, and axiological dimensions, brings the conceptual profile of substance further by recognizing the underlying differences between different ways of thinking/speaking about substance, thereby advancing what Silva and Amaral (2013) proposed as the first approximation of a conceptual profile of substance.

Some conceptual profile zones were robust in terms of the extensive emergence of the commitments from the three genetic domains. Of the six zones, four were extensively found in three genetic domains, but two were not so robust, because they were only minimally found in short interactions in formal learning environments (microgenetic domain). The sensorialist, functionalist, naturalist/artificialist, and compositionist zones presented a relative richness of evidence from the secondary data (from the sociocultural and ontogenetic domain) and ways of speaking (from the microgenetic domain) that allowed the characterization of the commitments that stabilize them. However, two conceptual profile zones, essentialist and interactionist, were not as extensive in this regard. Each zones had some commitments that were more salient than others. For example, the compositionist zone was easily constructed because its ontological commitments were very evident in the sociocultural, ontogenetic, and microgenetic domains; however, the axiological commitment of this zone was difficult to identify because neither the secondary data nor the ways of speaking provided robust evidence for it. Another interesting case was the identification of the interactionist zone's ontological, epistemological, and axiological commitments. It was not straightforward to identify these from secondary data and to elicit them from ways of speaking in the three genetic domains. In addition, due to process philosophy (Whitehead 1978) being a relatively contemporary philosophical school of thought compared with ancient philosophies (e.g., essentialism, natural kinds, and compositionism), sources of secondary data in the sociocultural domain were relatively limited to better characterize interactionist ways of thinking. The exploration of both the ontogenetic and microgenetic domains in this regard was also constrained by the paucity of evidence in students' ideas about substance as dynamic entities. Others have also encountered this difficulty (Amaral et al. 2018; Ngai et al. 2014; Talanquer 2018). Amaral et al. (2018) did not find evidence that middle school students talked about, nor developed ideas about, properties of substances as emergent during a teaching learning sequence of substance in the chemistry classroom. Similarly, Ngai et al. (2014) and Talanquer (2018) described students' assumptions about interactionism views in a less robust way than the other major assumptions in the hypothetical learning progressions of chemical identity and structure–property relationships, respectively. They pointed out that students struggle to conceptualize an emergent view of properties.

Rather than conceiving the conceptual profile zones of substance as a hierarchical set of ways of thinking which progress from everyday to scientific meanings, which was the lens that Silva and Amaral (2013) used to categorize them, they are seen as a set of ways of thinking that are grounded in a hierarchical genesis; i.e., some conceptual profile zones are more likely to emerge in early stages of a person's life while others are constructed from experiences (including school) that occur in later stages. For instance, in early stages when a child begins interacting with materials and classifying them based on their shape, texture, size, etc., the sensorialist zone is likely to start being conceptualized by the child. During subsequent years of the child's life, the naturalist/artificialist zone might begin being conceptualized upon realizing the existence of different sources where materials can be found or produced. The genesis of the conceptual profile zones is different for each individual because this genesis depends on an individual's cultural background and the contexts in which experiences occur in her life. For instance, a child who lives in a rural area and is more in contact with nature has different experiences than a child in an urban setting who is closer to industrialized materials.

It is not only the genesis of conceptual profile zones that is affected by the cultural background and contexts in which an individual has different experiences, but also the relative prevalence of each way of thinking that a person can exhibit in her conceptual profile of substance (Dawson 2014). From our study of the microgenetic domain, the compositionist and the sensorialist zones were the major constituents of the participating teachers' and students' conceptual profiles of substance in the present study. One of the possible ways to explain the prevalence of these zones is through considering that learning chemistry involves the development and application of chemical knowledge and theoretical and experimental practices to analyze, synthesize, and transform substances with the overarching goal of benefiting modern societies, along with the caveat that sometimes the application of chemical practices have led to serious and current environmental issues (Sevian and Talanquer 2014). According to Sevian et al. (2015), the current paradigm that guides the practice of chemistry relies on the idea that substance is a macroscopic–submicroscopic system that can be identified or characterized by observing/measuring a set of unique properties (such as melting point, boiling point, color), as well as by determining its chemical structure via spectroscopic means. Therefore, the practice of the identification and characterization of substances is quite related with the sensorialist way of thinking, which is based on conceiving substances as distinct classes of stuff with different perceivable properties (shape, color, texture, mass, smell, volume, taste, etc.) which are identified by the senses or through instruments. On the other hand, the practice of determining the chemical structures of substances has bestowed upon chemistry education a universal view that substances are either contained in objects/stuff or containers of particles, such as atoms, molecules, ions, etc. (Chang 2011; Hacker 1979), which is directly related to the compositionist way of thinking that was commonly exhibited in the teachers' and students' conceptual profiles of substance.

Several students and teachers exhibited more than two conceptual profile zones while engaging either in the interview or in the T-tC activity, which implies that several ways of speaking and thinking about substance coexist in their conceptual profiles. This finding has been recurrent in other research studies related to the development of conceptual profiles for different scientific concepts (Aguiar et al. 2018; Amaral et al. 2018), in which students share different ways of speaking-ways of thinking about a given scientific concept in a single statement, when solving a questionnaire, when engaged in an interview, or when learning science during a teaching and learning sequence. The relevance of the term "profile" in this theory is crucial in this research to understand that each person has a unique conceptual profile of substance, and that the zones an individual exhibits depend upon social language and the particular contexts where social interaction occurs. For instance, Padilla et al. (2008) reported that university professors presented different relative heights of the zones that constituted their conceptual profile of amount of substance. Some professors considered that a perceptive/intuitive way of thinking (amount of substance is defined as the "chemist's dozen") based on impressions and intuitions from everyday life experiences about amount of substance was more productive than a rationalist one (amount of substance defined in terms of number of elementary entities based on only considering the atomic-molecular level) when teaching and learning the mole concept. Thus, ways of thinking and speaking that are prevalent in the classroom can depend on what the teacher thinks is more productive for her students to use when solving problems or making sense about a given phenomenon.

The fact that students and teachers exhibited several zones in their conceptual profiles in interviews and the T-tC activity is a pertinent finding to highlight the different ontological, epistemological, and axiological categories that individuals can have in their conceptual profile of substance. For instance, when trying to define substance, Ilovecats (a student) exhibited the sensorialist and functionalist zones through one of her ways of speaking ("Because it's both physical and can be felt, and a scientist can do experiments around that to reveal its properties"). Ontologically speaking, it can be said that the sensorialist way of thinking that Ilovecats demonstrated is grounded in the ontological category of matter, but the functionalist zone that Ilovecats had in her profile is stabilized by the ontological category of process (Chi et al. 1994). The presence of both zones in Ilovecats' definition of substance is germane to the dynamic model of ontological knowledge (Gupta et al. 2010). The ontological commitments that are one of the three stabilizers (the other two being epistemological and axiological commitments) of her multiple ways of thinking are (a) flexible, because the student moved across her ontological categories to define substance, and (b) connected, because theoretically they can form a network of ontologies that was activated in specific contexts. This is a powerful finding—it confirms that experts are not the only ontological sailors when navigating concepts in chemistry, students also are. However, the difference between an expert's and a student's move across ontological categories is that the former is conscious of the existence and context-dependent power the explanations based on those ontological categories (as well as epistemological and axiological categories), while the latter might not reach such consciousness yet (Mortimer 1995).

Consciousness by students of their individual ways of thinking is essential, and this occurred to great extent in the T-tC activity when it was implemented in the chemistry classrooms. When Apricot asked the group, "Is everything on the periodic table a substance?" in Red5's classroom, he was trying to make sense of the difference between his definition of substance ("something you have to be able to see, and also, like, and if you can see it, it has to be something that you have to be able to touch") and the canonical understanding. Likewise, Soul (another student) relied on the sensorialist zone, but not all students agreed with his way of thinking about substance in that context. In response to this, Experiment asked "But how we know we are right?"; i.e., How do we know what way of thinking about substance is appropriate to explain that "everything in the periodic table is a substance"? The answers could have multiplied, e.g., because all these elements are either naturally occurring or synthesized by chemists; because several elements are used by people in daily life; because all elements have a set a unique of physical and chemical properties; etc. All these hypothetical discourses need to be in dialog to determine their pragmatic value in specific contexts to address the students' learning needs and to foster students to develop sense-making dialog for themselves.

Being aware of the pragmatic value of each conceptual profile zone depending on the context is transcendental to consider the zones as tools for making sense of the world. Analogous with the idea of *models of* versus *models for* (Gouvea and Passmore 2017), ways of thinking about substance are modes of knowledge, but their development and use in context involve enacting chemistry practices. For that reason, the conceptual profile zones of substance must be defined in more context-sensitive ways that highlight what those ways of thinking about substance are for. Ways of thinking about substance are not the end-products of conceptualizing a concept, they are ontological, epistemological, and axiological tools that individuals can use to raise new kinds of questions and new ways of looking at phenomena. For instance, a recent experience that involved the first author illustrates this. A couple of students in a local high school found an unknown substance (which was unlabeled) in the cabinet of their chemistry teacher's classroom. The students used a sensorialist way of thinking about substance to start predicting what that unknown substance was. Based on their compositionist zone of substance, they asked their chemistry teacher about the possibility of reaching out to a chemistry graduate student in a local university to do some spectroscopic tests to figure out what the substance was made of. When the students spent time analyzing the substance further in the laboratory at the university, they also relied on the interactionist zone: one of these students suggested studying the behavior of the unknown substance when it was put in contact with other substances. In this example, the students selected different zones to think about substance when identifying what the unknown substance was as they solved a chemical identity question.

To learn chemistry is to be introduced to different ways of thinking about and transforming to explain and predict, but also to design and evaluate, the natural world (Sevian and Talanquer 2014). The chemical knowledge and practices that students learn in chemistry are effective partners with students' everyday knowledge and practices. Students not only construct a repertoire of ways of thinking from previous experiences but also from new facts and experiments that do not necessarily depend on previous knowledge because they differ ontologically, epistemologically, and axiologically from what they know already (Mortimer 1995). Having a heterogeneous conceptual profile of substance means for students an opportunity to be aware of their own ways of thinking in order to interact with people from different spheres.

5 Conclusions and Implications

While there are six zones in the conceptual profile of substance, it was found that the sensorialist and compositionist zones were the most predominant in the subset of chemistry classrooms that were further analyzed to represent the heterogeneity of thinking about substance. It is therefore worth asking: Is the emphasis of teaching and learning substance through the sensorialist and compositionist ways of thinking productive to understand chemistry as a practice? Why are the functionalist, naturalist/artificialist, essentialist, and interactionist ways of thinking about substance less developed and used in chemistry high school classrooms? Are students missing important opportunities to better grasp what the practice of chemistry is? Chemistry itself is polysemous (Freire et al. 2019), and in general, chemists use all zones available when acting on the world. Therefore, this is likely true of the conceptual profile of substance. An example from the practice of organic chemistry is a useful example of this point. Organic chemists are interested in potential substances that can be used as medicines, polymers, preservatives, etc., for the benefit of humankind (functionalist zone). They classify these as natural or synthetic in order to describe whether they are doing extraction from plants or production of the substances in chemistry laboratories (naturalist/artificialist zone). They pay attention to the interactions of substances that occur or can happen during the extraction with organic solvents or during synthesis reactions with other substances in order to control those processes (interactionist zone). Once organic chemists purify a substance of interest, they characterize this substance through spectroscopic techniques in order to elucidate its chemical structure (compositionist zone), as well as by measuring physical properties that are unique and belong to the substance of interest (sensorialist zone). When reporting the synthesis or extraction of the substance at a conference or in a research article, organic chemists explain the mechanism of the processes based on conceiving that one single molecule of each system involved in the processes (substance of interest, solvents, reagents, etc.) has several properties of the whole system (essentialist zone).

How can chemistry teachers and educational researchers move ahead with the challenge of how to leverage the four zones that are present in society? The conceptual profile offers a mechanism to accomplish this. The ways of thinking about substance reported in the present study must be put in dialog in chemistry classrooms to better understand the practice of chemistry in those learning settings. It is when this dialog occurs that the students can see the relationships and contrasts that exist between chemistry and the experiences they have from different settings (for instance, home, classroom, laboratory, and social media). The ways of thinking about substance can be powerful mediators for students and teachers to make sense about phenomena by being aware of the repertoire of different ways of thinking and speaking about substance and the relative explanatory power that each of these has depending on the context.

Chemistry is filled with models that have limited utility, and chemists and therefore instruction tend to use models simultaneously to better extract predictions and explanations to support synthesis, analysis, and evaluation in the practice of chemistry. For example, de Vos and Pilot (2001) clarified the many layers of models used by chemists and taught in chemistry regarding acids and bases. Substance is another central concept of chemistry that bears clarification for the purpose of teaching. To better illustrate what ways of thinking about substance can be powerful mediators for students and teachers to make sense about topics in chemistry classrooms, some places where substance are central to the content that is universally taught in chemistry classrooms can be suggested for teaching interventions. For example, taking one of the recommendations of Ngai and Sevian (2017), learning about solubility is a powerful means to reveal information about the identity of a substance.

As a first possible step, students can first classify substances to predict whether a substance will dissolve in different solvents, and to what extent. Two categories of classification might be ionic and molecular. In order to classify solid substances, students can use their sensorialist way of thinking to identify whether the solids have sharp edges or soft textures. Students can also use their compositionist way of thinking to consider the unit cell of an ionic substance or the crystal structure of a molecular substance to think about how its composition may relate to how it dissolves it in another substance. The essentialist zone can be a productive way of thinking to determine whether a molecular substance is polar or not polar by looking at the composition and structure of a single molecule to qualitatively compare dipole moments of different molecules. Students can also use their interactionist zone to think about the extent to which a substance will dissolve in another substance by considering both energetic and entropic factors of internal potential energy between molecules and the number of different configurations in that molecules in undissolved and dissolved states may adopt.

6 Limitations

This research study contributes to the research program on conceptual profile theory, specifically supporting the transcendence of the heterogeneity of speaking and thinking about substance in chemistry classrooms. Nevertheless, the study has several limitations. One has to do with the approach employed to build the conceptual profile of substance. The approach used in the present study consisted of first exploring the sociocultural and ontogenetic domains to initiate inferring the conceptual profile zones of substance, and then fully developing them from the dialogical analysis between those partial zones and the empirical data generated from the microgenetic domain. It is possible that there was bias in the interpretations of primary data from a partial and non-intentional deductive analysis. This has been identified previously as an intrinsic limitation of studies of conceptual profiles that depart from the sociocultural domain (Mortimer et al. 2014). Regarding the published studies in which secondary data were collected, it represents a limitation that only Western history and philosophy of chemistry were consulted to explore the sociocultural domain. In the ontogenetic domain, some studies that were included were not carried out in schools that are culturally diverse and, in those cases, students' ideas about substance were limited to a defined sector of a population. Another limitation is the less robust ways of speaking and thinking related to the interactionist zone that were found from the three genetic domains. This limitation has an impact on both research and chemistry teaching. Regarding the impact on chemistry education research, it can be claimed that strategies that better elicit students' interactionist ways of thinking and speaking are needed. It is important for researchers to pay attention to the design of questions that effectively trigger the use of interactionist ways of thinking about substance by students. Based on the axiological commitment of this zone, the use of simulations in questions about what substance is might be a productive tool to generate contexts to talk about substances in interactionist ways. Regarding the impact on chemistry teaching, it can be asserted that the scarcity of examples of ways of speaking related to the interactionist zone might limit chemistry teachers' noticing of students' interactionist ways of thinking. However, the ontological, epistemological, and axiological commitments associated with the interactionist zone identified in the present study can guide chemistry teachers in designing activities that target a specific commitment that student need to socially develop to start or strengthen their speaking and thinking about substance in an interactionist way.

Acknowledgments The authors are grateful to the teachers who welcomed us into their classrooms to observe, collect student work, and interview them and their students. The first and second authors (R.O.P. and H.S.) acknowledge the funding source that supported this work: United States National Science Foundation award DRL-1621228. Also, the third author (E. F. M.) acknowledges the funding source that supported this work: Conselho Nacional de Desenvolvimiento Científico e Tecnológico awards 305205/2015-3 and 437439/2018-6.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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