On Cognitive Constraints and Learning Progressions: The Case of 'Structure of Matter'

Abstract

Based on the analysis of available research on students' alternative conceptions about the particulate nature of matter, we identified basic implicit assumptions that seem to constrain students' ideas and reasoning on this topic at various learning stages. Although many of these assumptions are interrelated, some of them seem to change or lose/gain strength independently from one another. Overlapping or competing presuppositions about the structure, properties, and dynamics of matter may be able to coexist at any given level, particularly at intermediate stages of expertise. Our results allowed us to suggest common paths in the transition from naïve through novice to expert along relevant dimensions related to the structure and properties of chemical substances. The identification of these cognitive constraints provides a useful framework that educators can use to better understand and even predict many of their students' learning difficulties. It can also assist in the design and organization of learning experiences and assessment tools that recognize and take advantage of the most likely trajectories towards expertise (learning progressions) followed by many students.

Introduction

Research in cognitive science and science education over the last three decades has given rise to a large body of empirical and theoretical results about students' ideas of the physical world. In particular, work in developmental psychology seems to support the view that the human mind operates on the basis of a small number of cognitive constraints that guide learning in specific domains (Sebastià, 1989; Siegler & Crowley, 1994; Wellman & Gelman, 1998). Several authors have argued that such constraints are organised in systems of knowledge (explanatory frameworks) that have some, but not necessarily all, of the characteristics of a theory (Vosniadou, 1994). Explanatory frameworks are conceived as a network of pre-stored, interrelated beliefs about the natural world, such as the idea that physical objects are solids and move in continuous trajectories, which constrain the types of mental models and explanations that people might construct. Other authors support the view that our intuitive knowledge about the world is more fragmented, comprised of a large, diverse, and moderately organized collection of phenomenological ideas, commonly referred to as p-prims (diSessa, 1993); examples of p-prims include notions such as "the closer the source, the stronger its effect." From the standpoint of researchers within the 'explanatory frameworks' tradition, conceptual change involves the revision, modification, or replacement of an individual's naïve theories and mental models (Carey, 1985; Vosniadou, 1994; 2007). The same process is conceived as one of reorganization and integration of cognitive resources by researchers within the 'knowledge in pieces' camp (diSessa & Sherin, 1998).

Despite differences in claims about coherence and level of integration of our intuitive knowledge, most researchers in the field of concept development and conceptual change refer, in some way or another, to tacit or implicit presuppositions (Vosniadou, 1994), core hypothesis (Chi, 2008), background assumptions (Vosniadou, 2007), phenomenological primitives (diSessa, 1993, 2006), core intuitions (Brown, 1993), or conceptual resources (Redish, 2004) that guide or support thinking in a domain. From this perspective, they seem to adhere to the view expressed by many cognitive scientists and developmental psychologists who consider that learning and reasoning are 'constrained' (Gelman & Williams, 1998; Hatano & Inagaki, 2000; Keil, 1990). Here, the term 'constraints' refers to elements of a knowledge system that guide and facilitate cognitive processes as well as restrict their possible range.

In general, cognitive constraints are assumed to be skeletal in nature (Gelman, 1990); they guide and restrict thinking but do not need to be fully satisfied. Reasoning in a given area seems to involve the activation or instantiation of a spectrum of constraints, from domain-general to domain-specific, from implicit to explicit, which are satisfied simultaneously as well as they can be. The goal is not necessarily to achieve conceptual coherence, but rather local explanatory coherence during a specific task in a determined context (Sloman, 1996). Constrained knowledge systems allow us to make reasonable, adaptative inferences about the world given limited time and knowledge (Gigerenzer & Selten, 2001). They often generate acceptable answers with little effort, but sometimes lead to severe and systematic biases and errors.

In our previous work we have argued that core learning constraints in a given domain can be conceived as sets of interrelated implicit assumptions about the properties and behaviour of the relevant entities in the domain, together with associated reasoning strategies to build explanations and make predictions and decisions with limited time and knowledge (Talanquer, 2006, 2008). Many of these reasoning strategies rely heavily on prior content knowledge and contextual cues to support predictive inferences. The unconscious activation or instantiation of these constraints in problem-solving or decision-making can lead to answers or explanations that may appear incoherent from the scientific point of view, but may reflect rational adaptations. This type of reasoning introduces variability in the explanation and decision-making patterns of a given person or among individuals who may hold similar assumptions and reasoning strategies. For example, when an unexpected event occurs, implicit assumptions about causal agency (Andersson, 1986) in combination with associative reasoning (Einhorn & Hogarth, 1986) lead us to search for a cause that is close in space and time, and that is familiar and thus easy to recall (if we have a stomach ache, we commonly think about what we ate; we search for a cause that is close both in time and proximity). The salient cues that any given individual uses in order to explain the phenomena are influenced by the particular context of the problem they are facing and by their prior knowledge. Thus, different people may select different cues to guide their reasoning about a phenomenon and generate different explanations, even though they may be guided by similar cognitive constraints.

The identification of students' implicit assumptions and reasoning strategies in a given area, as well as the characterization of how these constraints evolve with learning or development, can help us better define learning progressions that describe how students gain expertise in a given domain (Smith, Wiser, Anderson, & Krajcik, 2006). These learning progressions are useful tools in the design of educational materials and experiences that foster meaningful learning, as well as in the development of assessment practices that set clear standards of performance, properly track student progress, and provide formative feedback (Wilson & Bertenthal, 2005; Wilson & Scalise, 2006; Wilson & Sloane, 2000). From this perspective, the central goal of this research study was to characterize the core implicit assumptions that may constrain students' ideas and reasoning about the structure of matter at different learning stages. We were particularly interested in the development of a theoretical framework based on the analysis of cognitive constrains that could be used to explain and predict student thinking, and help develop a learning progression for the topic of structure of matter.

Knowledge Base and Guiding Assumptions

Students' alternative conceptions and models about the structure of matter and its changes have been the object of a large number of research studies in the past 30 years. In fact, this may be one of the topic areas in which the description of students' ideas at different learning stages may be best characterised. We have access to the results of not only original research studies that have targeted groups of students at specific grade levels (Duit, 2007), but also longitudinal and cohort studies that have explored the progression of core ideas from one educational level to another (Andersson, 1990; Jiménez Gómez, Benarroch, & Marín, 2006; Johnson, 1998; Liu & Lesniak, 2005; Liu & Lesniak, 2006; Margel, Eylon, & Scherz, 2008; Nakhleh & Samarapungavan, 1999; Nahkleh, Samarapungavan, & Saglam, 2005; Novick & Nussbaum, 1981; Renström, Andersson, & Marton, 1990; Pozo & Gómez Crespo, 2005). There are also a variety of monographs, books, and book chapters (Barker, 2000; Driver, Guesne, & Tiberguien, 1985; Driver, Squires, Rushworth, & Wood Robinson, 1994; Pozo & Gómez Crespo, 1998; Stavy, 1995; Taber, 2002), as well as review papers (Garnett, Garnett, & Hackling, 1995; Knerl, Watson, & Glažar, 1998; Nakhleh, 1992) that present surveys and analyses of research related to the development of students' models of matter.

Overall, existing research studies reveal strong commonalities among students' intuitive views of the structure of matter, as well as consistent changes in their ideas as a result of formal instruction. For example, most novice learners represent substances as continuous and static entities, and many of them generate hybrid continuous-corspuscular models of matter during the initial learning stages (Driver et al., 1994; Johnson, 1998; Resnström et al., 1990). However, these investigations also indicate that students' responses are strongly situated and may likely be influenced by the perceived physical appearance of the substances or materials investigated, or by the type of physical or chemical change that is analysed (Nakhleh et al, 2005; Pozo & Gómez Crespo, 2005). It is also true that, despite instruction received on the kinetic-molecular model of matter, a significant number of students seem to uphold naïve or common sense views about matter, its structure, and its changes. Thus, one may expect to find significant variability in students' ideas about matter even within the same grade level. From this perspective, it could be difficult to build a learning progression for the topic of structure of matter based on stages that are tightly linked to particular grades or educational levels.

Despite the apparent fragmentation and task-dependence of some of students' ideas about the structure of matter, the present work was guided by the assumption that student thinking at different learning stages may be thought of as constrained by implicit assumptions that can be inferred from the analysis of students' descriptions and representations of different types of substances and their changes. We also assumed that existing results on students' alternative conceptions and models about the structure of matter can be used to map both the common implicit assumptions that may constrain student thinking in this area and the evolution of these assumptions with instruction and learning.

Goals and Methodology

The present study was designed to address the following research question:

- *What core implicit assumptions may constrain students' ideas and reasoning in the micro-domain of "structure of matter" at various learning stages?*

To answer this question we have drawn on the vast number of research studies that have been published on the topic of students' alternative conceptions about 'structure of matter' as listed in the previous section. We paid particular attention to longitudinal and cohort studies that have explored students' ideas at various grade levels, and to monographs and review papers that present a survey and analysis of research related to the development of students' models of matter. The corresponding research work was completed in several phases:

Phase One: A comprehensive inventory of students' alternative conceptions and models about structure of matter was built based on the analysis of published research in this area. We focused our attention on those ideas held by a large proportion of students or those that seem to persist at different learning stages.

Phase Two: A wider review and analysis of developmental psychology, cognitive science, science education, and artificial intelligence research literature was completed to identify general beliefs, assumptions, intuitive rules or principles that have been characterised by other authors in the area of structure of matter, in related micro-domains, or in the wider domain of naïve physics. The analysis of these works allowed us to build a preliminary coding scheme based on a reduced number of categories describing core implicit assumptions.

Phase Three: The categories were used to build a classification matrix and coding scheme that was then applied to reorganise the set of common alternative conceptions and models described in the research literature. During this process, new coding categories were created and some of the initial ones were redefined. This analytical work allowed us to identify different areas or dimensions along which students' ideas about the structure of matter seemed to evolve with learning or development. It also allowed us to generate informed hypothesis about likely progressions in students' implicit assumptions along each of these dimensions.

Results and Discussion

Our analysis of the research literature on alternative conceptions about the structure of matter suggests that many of the ideas and models that students express or build at different learning stages may indeed be explained by the presence of implicit assumptions that have various levels of generality and evolve with learning. Table 1 summarises the core assumptions that were derived from our analysis; they have been classified into two major groups: Domain-General and Domain-Specific. Domain-general assumptions refer to constraints that may guide and restrict learning and thinking in different knowledge areas; domain-specific assumptions are mainly related to the topic under investigation. Within each of these two groups, constraining assumptions have been arranged into different types that indicate their area of application (e.g. categories, structure). For each of these types of assumptions, we depict the likely evolution of the constraints within that group; each sequence of constraints defines a dimension along which students' ideas may evolve. Comparison of reported students' models and ideas within and across grade levels indicates that full understanding of the current scientific model for the structure of matter involves comprehension of a set of ideas that, although interrelated, are not grasped simultaneously by most learners. Our arrangement of constraints in different types and dimensions is intended to highlight the possibility of their quasi-independent evolution with learning or development.

[Table 1]

The sequence of assumptions within a given dimension in Table 1 represents the most common path in the transition from naïve through novice to expert in the micro-domain of "structure of matter" as suggested by our analysis. Although the representation is linear, it does not imply that we propose that learning follows a linear path, that all individuals move sequentially through every stage, or that old assumptions fully replace new ones. On the contrary, our results support a learning or developmental model in which different assumptions within a given dimension may overlap and lose or gain strength depending on specific knowledge, contextual features, and perceived salient cues and goals in a given task. The relative influence of these factors on students' thinking seems to vary from situation to situation or even as time passes within a single task, which would explain the variability in an individual's explanations or predictions, particularly at intermediate levels of expertise where the number of overlapping assumptions multiplies. In the following subsections we describe the type of cognitive guidance and restrictions imposed by each of the constraining assumptions that were identified.

Constraints on categories

The analysis of students' models of the structure of matter and its behaviour indicates that their ideas are strongly influenced by the physical appearance of the objects, substances, or materials that they are asked to examine either in isolation or before and after they undergo a change. Thus, for example, novice learners are likely to build different models of matter for rigid solids versus powdery or plastic substances, to think of gases and liquids in more dynamic terms than they do of solids, or to conceive melting and boiling as two very different processes (Barker, 2000; Nakhleh et al, 2005; Pozo & Gómez Crespo, 2005).

These results suggest that, in the absence of requisite knowledge, naïve and novice learners' ideas and decisions about category membership and internal structure are constrained by the surface features and appearances of the objects or processes of interest. This domain-general 'surface similarity' constraint on the classification and analogical reasoning of children and novice learners has been described and analyzed by a variety of authors (Vosniadou &

Ortony, 1989). People's assumption about the existence of a direct link between the surface and deep properties of an entity is a powerful cognitive heuristic because in many cases surface features reveal deeper structural properties; in the real world, sensitivity to surface features has a high probability of paying off because appearances are usually not deceiving. Unfortunately, when it comes to the structure of matter, appearances are often misleading.

If novice learners' reasoning is guided by a 'surface similarity' assumption, one can expect them to hold or build similar structural models for entities that look similar to each other (e.g. all liquids), but not necessarily for those that exhibit different surface features (e.g. liquids vs. solids vs. granular solids). Our analysis indicates that paying attention to students' implicit categorisation decisions is of central importance in making sense of their analogies, models, and explanations, because a different set of domain-specific constraints may be activated or instantiated when considering entities that are perceived as belonging to distinct classes. For example, the same student may assume that solid materials are continuous and static while considering gaseous substances as particulate and dynamic (Barker, 2000). If surface features are relevant in making decisions about deep structure, one may expect novice learners' explanations to vary not only from one type of substance or state of matter to another, but also as their attention shifts from one salient feature to another during the analysis of the same system. This type of variability in students' models and ideas has been reported in the literature (Renström et al., 1990).

The reliance on surface similarities in making category membership decisions or in developing analogical explanations seems to decrease as learners acquire the necessary domain-specific knowledge. Advanced learners are more likely to use or develop models that can be applied across different classes of substances and states of matter, and generate explanations based on common structural and causal relationships at the particulate level (Johnson, 1998; Renström et al., 1990). One could argue that expert thinking about the structure of matter is guided by a 'structure similarity' constraint based on the assumptions that, no matter what differences in appearances and behaviours we observe, all substances share structural similarities at the particulate level and there are common causal mechanisms that determine their properties and behaviour. Reported research data suggests that the development of this way of thinking is not an easy task for many learners, and that people frequently rely on appearances as a fall-back in generating explanations about the structure and properties of matter when their knowledge or understanding is limited.

Constraints on structure

Students' ideas about the structure of matter have been organized in different categories, conceptions, or models by authors who have completed longitudinal or cohort research studies (Johnson, 1998, Nakhleh & Samarapungavan, 1999; Nahkleh et al. 2005; Margel et al., 2008; Renström et al., 1990). These classification systems share features that are revealing of the implicit assumptions that seem to constrain thinking about the structure of matter at various learning stages. For example, it is fairly well established that novice learners assume that matter is continuous, with no underlying structure. However, this *continuity* assumption loses strength as students are exposed to the particulate model of matter, and is overshadowed by the idea that matter is granular. The *granularity* assumption often becomes manifest in two main ways: either learners think of a substance as made up of little pieces of the same material or they think of it as continuous entity with embedded "atoms" or particles of some generic kind (Johnson, 1998; Renström et al., 1990). In either case, the actual substance or material itself (e.g. water, wood) is still conceived of as its main component.

A major transition in students' conceptualisations of the structure of matter occurs when they begin to conceive of a substance as a collection of particles with similar shape and size that are not further divisible into smaller particles of the same type, and that are characterised by specific attributes (such as a particular composition or structure). Under this *corpuscularity* assumption, the particles are no longer thought of as made of the substance or an undefined generic material, but instead the substance is conceived of as made of particles of a distinctive type. As we will see in the next section, this does not imply that learners that hold the corpuscularity assumption will stop attributing macroscopic properties to the particles that comprise the substance.

The shift from conceiving matter as a continuous and homogeneous medium to assuming that it is granular very likely introduces the need for an additional consideration regarding the nature of the medium between the granules or particles. Novice learners seem to presuppose the existence of some sort of material support in which the granules or particles are immersed, commonly air or the substance itself (*embedding* assumption). Research results indicate that the embedding assumption constrains learners thinking even after they develop more advanced ideas about the structure of matter (Pozo & Gómez-Crespo, 2005). This suggests that this presupposition may evolve independently of students' assumptions about the nature of the particles that comprise a substance. It is not until relatively advanced learning stages that students assume that the particles in a substance are separated by empty space (*vacuum* assumption).

Constraints on properties

Learners' explanation and prediction of the properties of substances also seem to be guided by implicit assumptions. Among them, a central thinking constraint is the assumption that the granules or particles that comprise a substance have the same properties of a macroscopic sample of the material (*inheritance* assumption). This presupposition leads learners to transfer many of the macroscopic properties of a substance to the submicroscopic level. A variety of authors have reported how students at various learning stages think that, for example, the atoms or molecules of a material expand when heated, or that they have the same density and color as the actual substance (Barker, 2000; Driver et al., 1994; Nakhleh, 1992). The inheritance assumption is strong and pervasive, and it influences constraints in other dimensions and categories.

One may argue that the inheritance assumption is a consequence of learners' granularity assumption about the structure of matter. If substances are thought of as made of little pieces of the same material, it is natural to assume that the parts will have the same properties as the whole. However, the inheritance assumption seems to remain as an implicit constrain in students' thinking even after learners develop more scientifically accepted views of the structure of matter. Results from studies of students' ideas about substances at different educational levels (Barker, 2000; Nakhleh & Samarapungavan, 1999; Nahkleh et al., 2005) indicate that many learners fail to recognize that new properties may emerge from interactions between multiple particles in a system (emergence). Thinking guided by this *emergence* assumption appears to be difficult to acquire, even when students have developed a good understanding of the structure of atoms and molecules.

Novice learners' explanations of the properties of substances and their changes also seem to rely on an additional presupposition: the *substantialism* assumption. This refers to learners' tendency to think of substances as the carriers of properties, such as color, smell, taste, hotness, fluidity, etc., and thus use the presence or lack of hypothetical substances to explain specific properties or changes in a material. For example, naïve students often explain changes in the color, smell, or temperature of a substance by reference to changes in the amount of a quasi-material entity that is the carrier of the property (Reiner, Slotta, Chi, & Resnick, 2000; Sanmartí, Izquierdo, & Watson, 1995); many of them also think that liquid substances contain water, the quintaessential liquid (Andersson, 1990).With the acquisition of more knowledge about the composition of substances, the *substantialism* assumption seems to evolve in some sort of "elementalism": the idea that chemical elements have some essential properties that are inherited by the substances in which they are present (Andersson, 1990; Nieswandt, 2001).

In general, our analysis suggests that one may expect novice and intermediate learners to conceive of substances as mixtures of some sort of elemental components and to explain the properties of these substances based on the relative amounts of the elements. Thus, implicit in both the substantialism and the elementalism assumptions is the belief that all of the properties of substances are additive, i.e., that they result from the linear combination of the essential properties of the elemental components of the substance of interest. Research evidence suggests that these types of assumptions are pervasive even among college chemistry students (Talanquer, 2008), and that learners frequently have serious difficulties understanding the macroscopic properties of substances not as preexistent in certain elemental entities, but rather emerging from the dynamic interactions of electrons in atoms, atoms in molecules, and molecules in macroscopic samples of materials (emergence assumption).

Constraints on dynamics

A variety of research studies (Barker, 2000) indicate that, in general, novice learners tend to think of the particles in a substance as fixed in space (*static* assumption). However, their ideas about particle movement seem to be influenced by the physical state and appearance of the substance under consideration. References to particle motion are more likely to occur when the novice learners identify an external agent acting on the object or substance (something that makes the object move or flow). This suggests that their thinking is guided by a domain-general constraint of causal agency: the idea that every change is caused by an external agent (Andersson, 1986). Thus, they assume that particles only move when they are forced to do so and that their movement will eventually cease (*causal-dynamic* assumption).

The assumption of continuous particle movement seems to first appear conditioned to the presence of perceptual properties or features, such as the temperature and state of matter of the substance, that suggest a sustained state of motion. Research results indicate that the more fluid-like the material is (liquid, gas) or the higher its temperature, the more likely the particles will be assumed to be moving (Barker, 2000; Pozo & Gómez-Crespo, 2005). This *contingent dynamic* assumption is somehow still indicative of the belief that all movement needs to be sustained, in this case by some internal factor such as the 'heat' in the material. It is not until later stages in learning or development that movement is assumed to be an intrinsic property of particles (*intrinsic-dynamic* assumption).

*Constraints on interaction*s

There is a large body of research literature in developmental psychology (Wellman & Gelman, 1998) that suggests that young children assume that interactions between objects only occur when they meet in time and space (*contact-interactive* assumption). Thus, one may expect novice learners to have a greater tendency to refer to interactions between particles in systems where they perceive that particles are in close contact, such as solids, than in less dense materials such as gases.

Even when students recognize the existence of ‘action-at-distance’, our analysis suggests that they condition the existence, nature, and strength of interparticle interactions to other factors (*contingent-interactive* assumption), such as the temperature and the state of matter of the substance, or the type of process it undergoes. Thus, novice and intermediate students likely think that the lower the temperature, the stronger the forces between particles, or that interactions become weaker, and even disappear, as we go from solid to liquid to gas (Brook, Briggs, & Driver, 1984). When they refer to forces between particles, they may think of them as repulsive or attractive forces depending on the nature of the substance or phenomenon of interest (repulsion may be used to explain the uniform distribution of particles in a gas, while attraction may be used to explain aggregation or condensation; Barker, 2000).

In general, learners seem to have serious difficulties assuming the existence of intrinsic forces between particles that only depend on the distance between them (*intrinsic-interactive* assumption). Research studies following the progression in understanding of the concept of intermolecular forces (Stevens et al., 2007; Stains and Talanquer, under review) indicate that a significant proportion of the students, from secondary to graduate school in chemistry, do not have a clear sense of the physical origin of the forces among particles in chemical substances, nor do they recognize the central role these forces play in determining the physical and chemical properties of materials.

Conclusions and Implications

Research in science education in the last thirty years has uncovered a vast number of students’ alternative conceptions in science. The reviews and summaries of this research have led to large lists of students’ ideas organised by discipline or topic. Unfortunately, this inventory-approach makes it difficult for teachers and instructors to identify any common presuppositions or patterns of reasoning that may guide students’ thinking about natural phenomena. Our analysis of students’ ideas about the structure of matter, as reported in the research literature, indicates that it is possible to identify a few implicit assumptions that seem to guide and restrict student thinking in this area. We suggest that this identification provides a useful framework that educators can use to better understand many of their students’ learning difficulties. It can also assist in the design and organization of learning experiences and assessment tools that recognise and take advantage of the most likely trajectories towards expertise (learning progressions) followed by many students (Smith et al., 2006).

From our perspective, focusing on the underlying implicit assumptions that constrain student thinking in a given micro-domain is a more fruitful educational approach than trying to address the myriad of specific alternative ideas and mental models held by the learners or generated during a given task. The alternative conceptions and mental models of diverse students in a given topic exhibit similarities that seem to be indicative of common underlying assumptions that constrain thinking in the domain (Sebastià, 1989). Variability in students’ responses and their sensibility to the context and specific nature of the task may be explained by assuming that the activation or instantiation of these cognitive constraints is highly dependent on judgments of similarity among systems or tasks (categorization of entities in different classes), cognitive availability (concrete memories of specific systems, events, or recent experiences), and framing of the system, event, or task based on contextual features, salient cues, and perceived goals.

The implicit assumptions summarized in Table 1 should not be conceived as a complete or closed set of constraints associated with students’ thinking about the particulate nature of matter. They represent the framework of a tentative theoretical model derived from available experimental results describing students’ ideas in this area. This model can be used to analyse, interpret, and even predict students' explanations and mental models related to the structure and properties of matter. As mentioned before, the analysis of the research data suggests that although assumptions along different categories and dimensions in Table 1 may be interrelated, some of them change or lose/gain strength independently from one another. We also contend that overlapping or competing presupposition within a given dimension are able to coexist at any given level, particularly at intermediate stages of expertise. With age, knowledge, and experience some assumptions may be activated or instantiated more or less frequently; they may also lose or gain strength depending on specific knowledge, contextual features, and perceived salient cues and goals in a given task.

The analysis of Table 1 suggests that although it might be possible to build good characterizations of the expected ways of thinking about the structure and properties of matter of novices and experts, the two extremes on the continuum of learning stages represented in this figure, it might be difficult to describe specific intermediate stages in a learning progression. Different students may advance at different rates along each dimension depending on their personal history, prior knowledge, and learning experiences. From this perspective, our results suggest that learning progressions may be better conceived as continuous road maps that allow for multiple paths towards expertise, rather than as a set of discrete steps describing more advanced ways of thinking.

References

Andersson, B. (1986). The experimental gestalt of causation: a common core to pupils' preconceptions in science. *European Journal of Science Education*, 8(2), 155-171.

Andersson, B. (1990). Pupils' conceptions of matter and its transformations (age 12-16). Studies in Science Education, 18, 53-85.

Barker, V. (2000). *Beyond Appearances: Students' Misconceptions about Basic Chemical Ideas.* Royal Society of Chemistry: London. Available at http://www.chemsoc.org/networks/learnnet/miscon.htm.

Brook, A., Briggs, H., & Driver, R. (1984) *Aspects of secondary students' understanding of the particulate nature of matter*. Children's Learning in Science Project. Leeds: University of Leeds.

Brown, D. (1993). Refocusing core intuitions: A concretizing role for analogy in conceptual change. *Journal of Research in Science Teaching.* 20(10) 1273-1290.

Carey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: MIT Press/Bradford Books.

Chi, M. T. H. (2008). Three kinds of conceptual change: Belief revision, mental model transformation, and ontological shift. In S. Vosniadou (ed.) *International handbook of research on conceptual change*. New York, NY: Routledge.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction*, 10, 165–255.

diSessa, A. A., & Sherin, B. L. (1998). What changes in conceptual change? *International Journal of Science Education*, 20(10) 1155-1191.

diSessa, A. A. (2006). A history of conceptual change research: Threads and fault lines. In R. K. Sawyer (ed.), *The Cambridge handbook of the learning sciences* (pp. 265-281). New York: Cambridge University Press.

Driver, R., Guesne, E., & Tiberghien, A. (1985). *Children's Ideas in Science*. Open University Press: Buckingham, England.

Driver, R., Squires, A., Rushword, P., & Wood-Robinson. V. (1994). *Making Sense of Secondary Science: Research into Children's Ideas*. Routledge: London.

Duit, R. (2007). *Bibliography STCSE: Students' and teachers' conceptions and science education.* Leibniz Institute for Science Education: Kiel, Germany: IPN. Available at www.ipn.uni-kiel.de/aktuell/stcse/.

Einhorn, H. J. & Hogarth, R. M. (1986). Judging probable cause. *Psychological Bulletin*, 99 (1), 3-19.

Garnett, P. J.; Garnett, P. J., & Hackling, M. W. (1995). Students' alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education.* 25, 69-95.

Gelman, R. (1990). First principles organize attention to and learning about relevant data: Number and the animate-inanimate distinction as examples. *Cognitive Science*, 14(1) 79-106.

Gelman, R., & Williams, E. (1998). Enabling constraints for cognitive development and learning: Domain specificity and epigenesis. In D. Kuhn and R. Siegler, (Eds.). *Cognition, perception and language*. Vol. 2. Handbook of Child Psychology (Fifth Ed). (pp. 575-630). WNew York: John Wiley and Sons.

Gigerenzer, G., & Selten, R. (2001). Bounded *rationality: The adaptative toolbox*. Cambridge, Ma: The MIT Press.

Hatano, G., & Inagaki, K. (2000). Domain-specific constraints on conceptual development. *International Journal of Behavioral Development*, 24(3) 267-275.

Jiménez Gómez, E., Benarroch, A., & Marín, N. (2006). Evaluation of the degree of coherence found in students' conceptions concerning the particulate nature of matter. *Journal of Research in Science Teaching*, 43(6) 577-598.

Johnson, P. (1998). Progression in children's understanding of a "basic" particle theory: a longitudinal study. *International Journal of Science Education*, 20(4) 393-412.

Keil, F. C. (1990). Constraints on Constraints: Surveying the Epigenetic Landscape. Cognitive Science 14(1) 135-168.

Knerl, D., Watson, R., & Glažar, S. A. (1998). Survey of research related to the development of the concept of "matter." *International Journal of Science Education*, 20(3) 257-289.

Liu, X., & Lesniak, K. (2005). Students' progression of understanding the matter concept from elementary to high school. *Science Education*, 89, 433-450.

Liu, X., & Lesniak, K. (2006). Progression in children's understanding of the matter concept from elementary to high school. *Journal of Research in Science Teaching*, 43(3) 320-347.

Margel, H., Eylon, B.S., & Scherz, Z. (2008). A longitudinal study of junior high school students' conceptions of the structure of materials. *Journal of Research in Science Teaching*, 45(1) 132-152.

Nakhleh, M. B. (1992). Why some students don't learn chemistry. Journal of Chemical Education, 69(3) 191-196.

Nakhleh, M. B., & Samarapungavan, A. (1999). Elementary school children's beliefs about matter. *Journal of Research in Science Teaching*, 36(7) 777-805.

Nakhleh, M. B., Smarapungavan, A., & Saglam, Y. (2005). Middle school students' beliefs about matter. *Journal of Research in Science Teaching*, 42(5) 581-612.

Nieswandt, M. (2001). Problems and possibilities for learning in an introductory chemistry course from a conceptual change prespective. Science Education, 85, 158-179.

Novick, S., & Nussbaum, J. (1981). Pupil's understanding of the particulate nature of matter: A cross-age study *Science Education,* 63(2) 187-196.

Pozo, J.I., & Gómez Crespo, M.A. (1998). *Aprender y enseñar ciencia* [*Teaching and Learning Science*] Madrid: Morata.

Pozo, J. I., & Gómez-Crespo. M. A. (2005). The embodied nature of implicit theories: The consistency of ideas about the nature of matter. *Cognition and Instruction*, 23(3) 351-387.

Redish, E. F. (2004). A Theoretical Framework for Physics Education Research: Modeling student thinking, in E. F. Redish and M. Vicentini (eds.), *Proceedings of the International School of Physics, "Enrico Fermi" Course CLVI*. Amsterdam: IOS Press.

Reiner, M., Slotta, J. D., Chi, M. T. H., & Resnick, L. B. (2000). Naive Physics reasoning; A commitments to substance-based conceptions. *Cognition and Instruction*. 18(1) 1-34.

Renström, L., Andersson, B., & Marton, F. (1990). Student's conceptions of matter. *Journal of Educaional Psychology*, 82(3) 555-569.

Sanmartí, N., Izquierdo, M., & Watson, R. (1995) The Sustantialisation of Properties. *Science and Education*, 4(4) 349-369.

Sebastià, J. M. (1989). Cognitive constraints and spontaneous interpretations in physics. *International Journal of Science Education*. 11(4) 363-369.

Siegler, R. S., & Crowley, K. (1994). Constraints on learning in non-privileged domains. *Cognitive Psychology*, 27, 194-226.

Sloman, S. A. (1996). The empirical case for two systems of reasoning. *Psychological Bulletin*. 119(1), 3-22.

Smith, C., Wiser, M., Anderson, C., and Krajcik, J. (2006). Implications of research on children's learning for standards and assessment: A proposed learning progression for matter and atomic-molecular theory. *Measurement,* 14 (1&2), 1-98.

Stains, M., & Talanquer, V. (under review). Using Classification Tasks to Characterize Learning Progressions: The Case of Intermolecular Forces. *Submitted to Journal of Research in Science Teaching.*

Stevens, S. Y., Shin, N., Delgado, C., Krajcik, J., & Pellegrino, J. (2007a, April 9 - 13). *Developing a Learning Progression for the Nature of Matter as it Relates to Nanoscience.* Paper presented at the American Educational Research Association, Chicago, IL.

Stavy, R. (1995). Conceptual development of basic ideas in chemistry. In S.M. Glynn and R. Duit (eds.) *Learning Science in Schools.* Hillsdale, NJ: Lawrence Erlbaum.

Taber. K. (2002). *Chemical misconceptions –prevention, diagnosis and cure. Vol I: theoretical background.* London: Royal Society of Chemistry.

Talanquer, V. (2006). Common sense chemistry: A model for understanding students' alternative conceptions. *J. Chem. Educ.* 83(5), 811-816.

Talanquer, V. (2008). Students' predictions about the sensory properties of chemical compounds: Additive versus emergent frameworks. *Science Education.* 92(1), 96-114.

Vosniadou, S., & Ortony, A. (eds.) (1989). *Similarity and analogical reasoning*. New York, NY: Cambridge University Press.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change, *Learning and Instruction,* 4, 45–69.

Vonsniadou, S. (2007). The conceptual change approach and its re-framing. In S. Vosniadou, A. Baltas, & X. Vamvakoussi (eds.), *Re-framing the conceptual change approach in learning and instruction* (pp 1-15). Amsterdam: Earli/Elsevier.

Wellman, H. M., & Gelman, S. (1998). Knowledge acquisition in foundational domains. In D. Kuhn & R. Siegler (eds.), *Cognition, perception and language*. Vol. 2. Handbook of Child Psychology (Fifth Ed). (pp. 523-573). New York: John Wiley and Sons.

Wilson, M., & Bertenthal, M. (Eds.) (2005). *Systems for state science assessment.* National Research Council. Washington DC: National Academy Press.

Wilson, M., & Scalise, K. (2006). Assessment to improve learning in higher education: The BEAR assessment system. *Higher Education, 52*(4), 635-663.

Wilson, M., & Sloane, K. (2000). From Principles to Practice: An Embedded Assessment System. *Applied Measurement in Education, 13*(2), 181-208.

Table 1

Implicit assumptions that constrain students' thinking about the structure of matter

Implicit Assumptions		
Domain	*Type*	*Dimension* *Novice* → *Advanced*
General	*Categories*	Surface Similarity → Structural Similarity
Specific	*Structure*	Continuity → Granularity → Corpuscularity Embedding → Vacuum
	Properties	Inheritance → Emergence Substantialism → Elementalism → Emergence
	Dynamics	Static → Causal-Dynamic → Contingent-Dynamic → Intrinsic-Dynamic
	Interactions	Contact-Interactive → Contingent-Interactive → Intrinsic-Interactive