Learning and Teaching about Matter in Grades K-8:

When Should the Atomic-Molecular Theory Be Introduced?

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(To appear in *The International Handbook of Conceptual Change*, edited by Stella Vosniadou)

Abstract

The atomic-molecular theory is one of the most important scientific theories and yet, current K-12 science teaching is typically not effective in helping students understand and accept it. Rather, the majority of students have many fundamental misconceptions about atoms and molecules, and fail to understand the central tenets of the theory, as well as its explanatory power. In this chapter, we place the atomic-molecular theory at the end of a learning progression for the macroscopic concepts of matter and materials, whose other end lies in infants' concepts of object and substantiality. This progression encompasses several fundamental conceptual changes for a broad range of inter-related concepts—not only matter and substance, but also weight, volume, density, solid, liquid and gas. Those conceptual changes are themselves inter-related with changes in mathematical and epistemological understanding—about the validity of perceptual data unmediated by measuring instruments, the nature of number and of measurement, and the role of theories and scientific models. We examine the nature of those conceptual changes, the difficulties they pose for many students, and the inadequate states of knowledge caused by those difficulties for students in different grade ranges. These analyses motivate considerations of curricular design and, in particular, where, in the learning progression, the atomic-molecular theory best fits. We conclude that it should be presented in late elementary-early middle school—late enough that the macrosocopic and epistemological knowledge necessary to understand it would be in place (given an effective curriculum), but early enough that it can contribute to further macroscopic conceptual changes about matter, i.e., to developing the concepts of gas and chemical substance.

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Marianne Wiser and Carol L. Smith

The atomic-molecular theory is one of the most important scientific theories, on par with Darwin's theory of evolution. It is important that it be familiar to students graduating from high school but, like evolution theory, it is highly counterintuitive for most students, and current K-12 science teaching is typically not effective in helping them understand and accept it. Rather, the majority of high school and even college students (including chemistry majors) have many fundamental misconceptions about atoms and molecules, and many fail to understand the central tenets of the theory, as well as its explanatory power.

Recently, researchers have begun investigating the deeper *reasons* for such failure. Significantly, their work suggests that difficulties with the atomic-molecular theory are only the tip of the iceberg. Lurking underneath are fundamental difficulties with conceptualizing matter and materials on a macroscopic scale as well as basic limitations in students' epistemological understanding of what science, and scientific models in particular, are all about. Thus, developing an understanding of the atomic-molecular theory will call for *more* conceptual changes (and also *more types* of conceptual changes) than has often been acknowledged. However, this does not mean that atoms and molecules should not been introduced relatively early in the curriculum, as those concepts interact with understanding matter at the macroscopic level. This raises obvious questions: Which conceptual changes should one work on with students during the elementary and early middle school years? Is there some set of macroscopic concepts and epistemological understandings that should be in place before introducing the idea of atoms? Are there other macroscopic concepts and epistemological understandings that are best developed in combination with learning about atoms and molecules or after those concepts are introduced? In other words, when is learning about atoms part of the problem and when is it part of the solution?

We will start by sketching out a learning progression for the concepts of matter, weight, density, volume, and material kind from early childhood to middle school, assuming traditional science and math instruction,[1] in order to identify students' state of content and epistemological knowledge at the time the atomic model is introduced (typically in eighth grade, in American schools). We will argue that how far students progress along this trajectory is more variable than commonly realized. For example, there is great variation in the modal patterns of thinking for different populations of students. Further, students in the same grade and in the same school system are often conceptually in quite different places. The reasons for these differences are not yet well understood. At a minimum, this variation shows that developing certain macroscopic conceptions of matter is not "developmentally" inevitable (as is commonly assumed) but critically depends on the instructional and other cultural experiences available to students and their degree of involvement in sense-making about these experiences.

We will then present the major misinterpretations students develop about atoms and molecules during the middle and high school years and discuss the diverse reasons for those misconceptions. These include the important role played by their (inadequate) macroscopic concepts and epistemological knowledge and the interactions among beliefs about atoms, macroscopic concepts, and epistemology. We will argue that a curriculum focused on helping students develop a core set of macroscopic and epistemological understandings during elementary school (e.g., understanding that all matter has weight,[2] model building in science, and so on) would provide students with important resources for making the atomic-molecular theory meaningful. At the same time, we will argue that learning about atoms and molecules early (by late elementary or early middle school) is important both because it helps consolidate macroscopic understandings about matter (e.g., the material nature of gases) and provides a necessary foundation for developing other important macroscopic understandings (e.g., evaporation; chemical reactions). Whether there are benefits to integrating modeling matter at a microscopic level even earlier in the curriculum remains an open question.

Assumptions Guiding Our Conceptual Analyses and Review

The concept of matter does not develop in isolation but rather in close interaction with the concepts of weight, density, mass, and material kind and, later on, with the concepts of atoms and molecules. We find both individual concepts and the broader network in which they are embedded useful units of analysis. Others (diSessa & Sherin, 1998) argue that it is more useful to focus on levels of description at the subconceptual level, in part because this level has greater “reality” and invariance; they interpret students in clinical interviews as constructing “on the fly” context-specific models of each situation presented to them by using subconceptual elements. They further argue that the structure of concepts is much more complex than has been acknowledged, that concepts have no simple core, and that conceptual change consists of gradual change in the tuning of cueing priorities for different subconceptual elements, rather than radical restructuring.

We do not deny that multiple levels of analysis are important; in fact, we embrace this view. As we will see, the literature on students’ beliefs about conservation of weight and matter, and about molecules and atoms, gives plenty of evidence for the context dependency of students’ assertions and for explanations being constructed on the spot during interviews. However, students’ thinking is not unconstrained. They bring to their interactions with the researcher interrelated epistemologies (the senses are good indicators of physical entities), ontologies (atoms are gas-like), intuitive theories (matter is what can be felt and seen) and models (atoms are embedded in matter), within which they then invent more specific explanations.

Conceptual change undoubtedly involves reorganization of subconceptual elements and progressive shifts in cueing priorities, which curricula should support. (e.g., from “if I can see the iodine gas, iodine is still there” to “even if I cannot see water vapor, it is still there because matter does not disappear”; or from “this grain of rice weighs nothing because it feels like nothing” to “it has to weigh something because it is matter; a very sensitive balance scale would show it”). However, these shifts are not simple belief revisions, they are part of conceptual and supraconceptual reorganizations and cannot be stabilized without large-scale restructuring. The scope and depth of the restructuring is what makes conceptual change difficult and therefore it is of great pedagogical relevance. What could be interpreted as a shift in cueing priority (e.g., from heft to balance scale) involves *concurrent and inter-related* changes in concepts (e.g., felt weight moves from core to periphery; weight becomes an extensive property), conceptual relations (any piece of matter weighs something; weight is differentiated from density), ontology and epistemology, as it would in scientific theory change.

Concepts do indeed have a complex structure (Keil & Lockhart, 1999), and their different aspects can be foregrounded in different contexts. We believe, however, they also have a core as well as less essential components; conceptual restructuring often involves movement from core to periphery and vice versa (Carey, 1991). But again, this movement is part of a change in ontology and epistemology: for example, felt weight becomes peripheral *because* students have come to appreciate that objective measures are more precise and reliable, and they support lawful generalizations (e.g., about the relation of weight and volume). This complex shift is also one in which a concept changes status from explanans to explanandum, a hallmark of theory change in science: Felt weight is primitive in students' early view of matter, whereas later it is accounted for by the scientific concepts of weight, pressure, volume, and density (as well as physiology). We consider that, in the domain of matter at the macroscopic level, the conceptual changes that bring students to a view of matter, weight, volume and density compatible with the scientific theory involve many characteristics of theory change in science.

The case of the atomic-molecular theory is different because few students have a concept of atom or molecule prior to instruction. Thus, learning the atomic-molecular theory is not a matter of revising one's pre-existing concepts and beliefs about atoms and molecules but about developing them in the first place. However, analyzing the beliefs that students develop about matter at the atomic level as a result of instruction also benefits from a multi-level approach because their interpretations are constrained by their macroscopic view of matter and their epistemology. Moreover, this approach allows us to distinguish between kinds of misconceptions. Not all misconceptions are born equal nor are they equally resistant to change. We will argue that some (e.g., that atoms are embedded in "stuff" or that they have all the properties of materials at the macroscopic level) are both prevalent and entrenched because they involve multiple reasons—conceptual, perceptual, metaphysical, or epistemological. They also seem to be ideas that students have developed as they were trying to make sense of information presented in the classroom prior to being interviewed. Others are more fleeting and appear created "on the fly" in an effort to answer the interviewers' probes, without deep commitment on the part of the students. This distinction is important for obvious pedagogical reasons and speaks to the concept/subconcept debate, as an analysis exclusively at the level of subconcepts might not allow for important distinctions between misconceptions.

The goal of this chapter is neither to document nor try to resolve the intuitive theory versus knowledge-in-pieces debate. The paragraphs above were intended to clarify the framework within which we are writing this chapter. As for the debate, we suspect that consensus will develop around some integrated version (as with Piagetian and Vygotskian approaches, or the trichromatic and opponent-process theories of color vision). As with all theoretical differences, this one will be resolved by making detailed proposals about the role of the different levels—perceptual, subconceptual, conceptual, ontological, epistemological—in constraining knowledge acquisition. Another component will be examining which framework best captures students' patterns of answers to the *same* problems in a variety of contexts, as well as which framework informs more effective teaching studies, and ultimately, curricula. We suspect that scientific domain may be important— students may have a richer network of concepts in some domains than others, which may place more constraints, and therefore produce more coherence, in their reasoning.

A Learning Progression for the Concept of Matter at the Macroscopic Level

The Early Development of the Concepts of Matter and Material Kind

Infants and young preschool children undoubtedly don't have any explicit explanatory concepts of matter or material kind. In order to have such concepts, children need to not only distinguish multiple levels of description (object, material kind, and matter), but also to inter-relate those levels into representations expressed by "Wood is a kind of material" or "This car is made of wood." Further, for these concepts to be explanatory, children need to use knowledge of properties at one level to explain properties at another. For example, “This cup breaks *because* it is made of glass,” or “I can see, feel, and touch this doll *because* it is made of some stuff.”

Although explicit concepts of matter and material kind are not present in infancy, their precursors do exist in the form of a concept of object, a concept of “non-solid” (encompassing liquids, aggregates, gels, and other nonrigid materials that in children’s experience allow dividing, molding, or pouring), and a sense of substantiality. There is abundant evidence that infants have a robust concept of physical object that they understand as a bounded entity, that is solid, permanent and enduring, and that has characteristic properties and functions (Baillargeon, 2002; Spelke, 1991). In addition, there is some evidence that, by 8 months, infants make a distinction between discrete objects (that are countable) and continuous entities such as liquids and aggregates (that are not) (Huntley-Fenner, Carey, & Solimando, 2002). This distinction plays an important role in early word learning. For example, even 2-year-old children generalize novel names of nonsolid aggregates to other portions of the same material shaped differently, whereas they generalize novel names of solid objects to other objects of the same shape even if they are made of a different material (Soja, Carey, & Spelke, 1991). Embedded in the notion of both solid objects and nonsolids is a notion of substantiality. Infants perceive properties such as shape, size, texture, and pliability intermodally; they expect things they see to lend themselves to be touched and handled and to interact causally with each other in ways that are constrained by their properties, spatial arrangements, and physical contact. We take this network of expectations to form the precursor of a concept of matter while the distinction between (solid) objects and nonsolids will lead to the distinction between objects and material kinds.

These precursors guide, and are enriched by, children’s explorations of the physical world and their interpretations of linguistic input. For example, sensory and motor experience with objects versus nonsolids entrenches the notion that the shape of (inanimate) objects is both invariant and relevant to one's actions on them, whereas it is texture (and other intensive properties) that are both invariant and relevant to one's handling of nonsolids. Language acquisition builds on this distinction—in languages such as English, object names are count nouns whereas names for material kinds are mass nouns—as well as helps them go beyond it as they learn that there are material kind names that label portions of both solid and nonsolid stuff.

Significantly, the first material kind names infants learn are for liquids (water, milk); children are somewhat slower to acquire material kind names for solid materials, although they usually have at least some names by ages 3 or 4 (Bloom, 2000). In Western children's experience, solid materials (cotton, wood, plastic) are more variable in color and texture than nonsolids (milk, water, sand). More crucially, nonsolid materials tend to be associated with unique patterns of sensory-motor experiences (e.g., Playdough has a specific texture and gets molded; milk is white, fluid, and for drinking) whereas it is the kind of object rather than the material it is made of that has the strongest association with sensory-motor activity. Thus, learning the names of solid materials not only requires overcoming the salient object-level description but also constructing the notion of "made of" and articulating the two—this is a spoon and it is made of plastic (Bloom, 2000). This, we propose, is a major and long-drawn conceptual change, drawing on multiple sources.

Linguistic input draws attention to the materials solids are made of, not just with the names of materials (plastic, glass), but also with statements like "This is a plastic spoon" or "This spoon is *made of* plastic." Using "plastic" as an adjective guides generalizations across different kinds of plastic objects and thus encourages linking "plastic" to shininess, lightness, and flexibility. We hypothesize that the combinations of such statements with nonverbal patterns of experiences in which objects made of the same materials have similar appearances and show similar behaviors (rubber objects bounce, glass objects break) help create initial concepts of material kinds for solid objects.

Children would then be in a position to establish similarities between solid and nonsolid materials. They are both characterized by surface appearance and texture, independent of shape and size of the object/sample, and correlated with how the object/sample interacts with other objects (e.g., when dropped, sand makes a pile, water makes a puddle, and rubber objects bounce). Linguistic input is also a factor in this process: the names of materials, whether solid or not, are embedded in the same grammatical construction ("This is sand," "This is plastic"). The role of similarity in fostering inference of additional common properties and thus in conceptual development is well-documented in Gentner's (2003) work. We hypothesize that, once children are aware of similarities between solid and nonsolid materials, the rich sense of what nonsolid materials *are*—that they have the same perceptual and motor affordances all the way through, gained from squeezing and running their hands through them as opposed to being limited to exploring the surface of solid materials—gets mentally applied to solid materials as well, giving "made of" a deeper meaning. (It is also possible that children have enough familiarity with cutting and breaking solid objects to make this inference). Thereby a new ontological category is formed—material kind—encompassing the materials of objects and nonsolids. When this new material kind level of description is coordinated with the object level of description, children can think of a plastic spoon both as a spoon (an object whose shape is designed for eating) and as made of plastic. It is likely that an essentialist bias makes material kind an explanatory concept—this breaks *because* it is made of glass, this bounces *because* it is made of rubber (Gelman & Markman, 1987). At the same time, infants' sense of substantiality is enriched and becomes the core of young children's concept of matter: things that are seen, touched, and hefted, are now conceived of as made of stuff, in the sense described above.

Evidence for understanding material kind. There are several lines of evidence that children between 3 to 7 years of age are developing concepts of specific materials kinds as well as more general concepts of matter and material kind. Those developments are complementary and mutually supportive. First, preschool children not only are learning the names for many kinds of objects, but also for particular kinds of materials. We take the onset of learning material kind names for solid materials and children's ability to answer questions about what kind of stuff objects are made of as good evidence that they are formulating explicit concepts of material kinds at this time (Bloom, 2000; Dickinson, 1987, 1988).

In addition, young children are beginning to distinguish explicitly between properties that may characterize particular materials (e.g., sweetness, color, texture) from properties that characterize particular objects (e.g., shape, size, function). In an unpublished study, Wiser gave 3- and 4-year-olds pairs of unfamiliar objects (A and B) to hold. The objects were made of different (unfamiliar) materials of significantly different densities and were given unfamiliar labels ("This is a dax and that is a tiv"). Children were asked which one was heavier. Then another pair was placed before the child, the same two shapes but made of the opposite material, and the child was asked, "Which one is a dax?" and "Which is heavier?" The children performed significantly differently on the two questions, showing a stronger association between shape and name and between material kind and heaviness, respectively. In other studies, preschool children made distinctions between properties that varied with the amount or size of the sample (e.g., is big, can be blown away) from properties that characterized the specific material (e.g., is sweet, burns, is white) (Au, 1994). Although children were not as good as adults, the fact that most were above chance in patterns of responding is consistent with their making some distinction between these two levels of description.

Third, 4- to 6-year-old children know that when a paper cup or a wooden airplane is chopped into pieces, the pieces are still paper or wood but no longer a cup or airplane (Smith, Carey, & Wiser, 1985). This gives further evidence that they distinguish object and material levels of description and have contrasting ways of tracking the identity of objects and materials. This is likely to be because the pieces still have the characteristic (perceptual) properties they associate with the material rather than because they have a deep belief that breaking or grinding does not change material kind or think of material kind as an *underlying* constituent. Evidence for this interpretation comes from the fact that younger children are more likely to justify their judgments by saying that it still *looks like* wood, rather than arguing that it is still wood because that was what it was made of (Smith et al., 1985).

Evidence for understanding of matter. The prior studies suggest young children are developing some concept of material kind that is distinct from their concept of object kind. But what evidence is there that they might also be developing some general concept of matter and recognize that there are important commonalities across different materials? And what might those commonalities be?

One of the most basic ontological distinctions, made explicitly even by preschoolers, is a distinction between physical and mental entities. In a series of elegant studies, Estes and Wellman found that 3-, 4-, and 5-year olds were able to judge that physical objects have a rich variety of “sensory-behavioral” affordances that thoughts of those objects do not (Wellman, 1990). For example, you can see, touch, and feel a cookie but not the thought of a cookie. Physical objects have a public and consistent existence that thoughts of those objects, which are private and fleeting, do not. Of course, making an ontological distinction between physical objects and thoughts does not require that children have an explicit concept of matter: They could be contrasting mental entities and entities with public existence, without representing solids, liquids, and aggregates as alike in that they are *made of some kind of stuff*.

Some direct evidence that they do have a more general concept of matter comes from a small-scale study by Carey (1991) in which 4-, 6-, 10-, and 12-year-old children were explicitly asked to sort entities into different piles: one pile for things that were made of some kind of physical stuff, one pile for things that were not made of some kind of stuff. Children were given a wide range of entities: solids (both inanimate physical objects and biological kinds), liquids (water, coca-cola), powders (sugar), gases (air, steam), nonmaterial physical entities (heat, electricity, shadows, echo) and mental entities (wish, idea). Carey found that about half of the 4-year-olds, three quarters of the 6-year-olds, and all the older children grouped some solids, liquids, and powders as alike in being made of some kind of stuff. Of course, none of these children had the scientists' concept that neatly picked out all solids, liquids, powders, and gases while excluding other nonmaterial physical entities. Indeed, they all made some under- and overextension errors (which we will return to discuss shortly). Nonetheless, the fact that they were making some sensible groupings at a level broader than solid physical object is evidence that preschoolers are developing a broader concept of matter. They not only recognize that these entities are things that can be seen, touched, or produce some physical effect but they use these properties as evidence that they are all "made of some kind of stuff."

A final piece of evidence that children are developing a more general concept of matter during this time is their increasing success with the classic Piagetian conservation of matter tasks (Piaget & Inhelder, 1974). In these tasks, children are given samples of different materials (a ball of clay, a beaker of water, a certain length of wire) and then watch while the sample is reshaped or divided into smaller samples (e.g., the clay ball is rolled into a sausage or divided into four pieces). Whereas younger children typically think the amount of clay, liquid, or wire has changed because of perceptual appearances, the majority of 7- and 8-year-olds make correct judgments. “Conservation of matter” is somewhat misleading, however, because it connotes the scientific principle that matter is conserved under all physical transformations. What children this age achieve is much more modest and might be better described as a concept of amount of material, which stays invariant if no material is added or removed during the transformation; that is how they generally justify their correct judgments.

Piaget and Inhelder originally explained this development in terms of the development of concrete operations, an account that has been heavily critiqued on both theoretical and empirical grounds. We prefer to view it as a domain-specific achievement, arising from an emerging naïve theory of matter, although our view shares with Piaget and Inhelder’s account the hypothesis that an early notion of composition and decomposition are part of this deeper understanding. To think of solids and nonsolids as constituted of homogeneous pieces of stuff is tantamount to having a sense of amount of stuff; adding or removing pieces change this amount, and if nothing is added or removed, the amount stays the same. We suspect it is no coincidence that children are distinguishing this unseen (theoretical) quantity, which is conserved from perceptual appearances (it looks different), during the same time that they are learning more about specific materials. They recognize that solid objects are made of something and come to see commonalities among solids, liquids, and powders in that they are all made of some kind of stuff. Further research is needed to establish the links among these developments in the same group of children across a variety of materials.

Summary of the development of matter and material kind in early childhood. We have proposed that the concepts of matter and material kind children bring to elementary school have their roots in infancy—in infants' concepts of solid objects and of nonsolids (aggregates and liquids) and in their sense of substantiality expressed in intermodal expectations that objects can be seen, touched, and handled. Generalizations based on experiences with a variety of objects, liquids, and aggregates, combined with lexical and syntactic input as well as analogical reasoning, foster the development of an intuitive theory of matter and material kind during the preschool and elementary school years. The domain of this theory is solids, liquids, and aggregates. Its core tenets are that matter can be touched, seen, and hefted; that it exists as different material kinds, which have perceptual and inherent properties that explain their behaviors when acted upon; and that its amount (a qualitative notion) does not change under visible mechanical transformations (change of shape, macroscopic division).

The emergence of this theory involves several related conceptual changes. Children coalesce physical objects and nonsolids into a new ontological category—made of "stuff"—that now accounts for the substantiality that was part of infants' perception of objects and nonsolid entities. Conceiving of solid objects as made of specific kinds of stuff allows the differentiation of object level properties and material kind level properties.

Unlike its scientific counterpart, the core of the concepts in children's intuitive theory of matter is perceptually based: An entity is material (made of some stuff) if it can be touched and seen. It can be thought of as composed of homogeneous parts that are touchable and visible as well or they could not compose matter, according to the criterion. The understanding of conservation young children evince in Piagetian tasks is based on this notion, evoked in the context of witnessed transformations. Other transformations, however, make "matter" disappear, most saliently boiling, dissolution, and burning. According to the intuitive theory, gases are not material. Material kinds are also identified perceptually, according to appearance and behavior (e.g., glass is transparent and breakable) so that, if melting and freezing significantly change the appearance and behavior of a material, they are taken to transform one material kind into another.

The kinds of conceptual restructuring needed to understand the macroscopic scientific theory of matter will be deeper and more complex than those involved in achieving the intuitive theory of matter. We will show in the next section that this conceptual restructuring involves a rich network of concepts (not only matter and material kind but also weight, volume, and density), deeper ontological changes, and radical changes in epistemology. Not surprisingly, the majority of students reach the end of middle school without a good grasp of the scientific concepts and epistemology.

Later Developments in Children's Concepts of Matter and Material Kind: Enrichment, Fragmentation, and (More Rarely) Restructuring

Given that young children’s initial concepts of matter and material kind are quite different from the concepts of matter and chemical substance that are the target of elementary and middle school science curricula, what happens when children are exposed to these curricula? How do their ideas (typically) develop and change? In this section, we propose that it is useful to distinguish changes that involve piecemeal elaboration of children’s initial concepts from those involving fundamental restructuring. Although some children make fundamental changes in their understanding of matter and material kind during this time, many others do not. Thus, exposure to new facts and information does not necessarily lead to deep (and productive) conceptual changes. Instead, the new information often produces only limited progress toward the scientific view, which, for reasons we explore below, falls severely short of the conceptual revisions necessary to master a macroscopic understanding of matter and material kind consistent with the scientific view. It can also lead to greater fragmentation, confusion, and conceptual incoherence in ways that are not widely recognized in the science education community, in part because this community has not been attentive to describing how students' concepts are articulated.

Knowledge of different kinds of materials and range of entities considered to be matter. During the elementary school years, the notion of material kind becomes more salient to children, as evidenced by a steady increase in using material kind in spontaneous classifications (Knerl, Watson, & Glazar, 1998). There is also an increase in the number of material kind names that children spontaneously generate when asked to give examples of what things are made of (Smith et al., 1985).

Two studies have investigated changes in children's judgments of what is and is not matter during the elementary school years (Carey, 1991; Stavy, 1991). Carey found that even first graders were significantly above chance in judging solids, aggregates, and some liquids to be matter, in keeping with our proposal that they think of matter as something they can see, feel, and touch. Further support for this assumption comes from their commonly referring to these properties when asked to explain how they could tell something is matter or what properties all matter might have. Stavy's first graders performed less well, possibly because, unlike Carey, she did not offer anchoring for the word "matter" by providing examples of prototypical material and nonmaterial entities (solids vs. mental entities). By 7th grade, the vast majority of children in both studies were correct in making judgments about solids, liquids, and aggregates, but there was less change in the frequency of children's overextensions to nonmaterial entities such as electricity, which remained substantial, and they were only at or slightly above chance in judging that air was matter. Even by 8th grade, many students still believe that air is not matter (Smith, Maclin, Grosslight, & Davis, 1997).

Given that children have explicitly been told that air is matter on numerous occasions, this underextension suggests that what they are told simply doesn't make sense, because it violates their concept of matter as something that can be seen, felt, and touched. Revising the ontology of gases requires a theory that provides uniting common properties for solids, liquids, and gases (e.g., having weight and taking up space); this theory cannot be achieved without extensive and radical conceptual restructuring, not only of matter but of weight and volume (as well as experimental evidence about the weight of gases). Quite strikingly, none of the younger children and only a few of the older children in the previous studies, used having weight as criteria for being matter (Carey, 1991; Stavy, 1991). In the absence of this restructuring, students can either reject that gases are matter, fragment their understanding of matter by introducing unexplained exceptions, give matter the unconstrained meaning of "everything that exists," or accept that "solids, liquids, and gases are matter" without understanding what "matter" really is, relying on similarity to prototypes of solids, liquids, and gases to judge whether something is matter or not.

Conceptualizing materials as underlying constituents. Young children's initial understanding of matter and materials is very much based on perception and action—objects (broadly defined) are "seeable" and tangible (matter), and they exist in a variety of kinds of stuff with certain clusters of perceptually accessible properties (material kinds). This understanding allows them to infer that both smaller and larger samples of a material have some common characteristics, but usually only when reasoning about sizeable chunks that share perceptual properties. Presented with a chunk of iron and the powder that they are told resulted from grinding it, 4-year-olds believe the powder is not iron because it does not look like the chunk (Dickinson, 1987).

A more advanced understanding of objects *being made of* a material is based on the notion of *underlying constituent,* that is, on conceptualizing and visualizing the object as being composed of very small pieces of the material all the way through. This early mental modeling may have its source in sensory-motor experience with aggregates (grains of sand, specks of dirt) and clay-like substances that can be broken into tiny pieces, extended by limiting case thinking. It allows older children to override perceptual dissimilarities and know that iron powder is still iron, because it is made of the same tiny pieces that constituted the chunk. Dickinson (1987) found that it is not until age 12 that most children *consistently* group powders with chunks for all the materials presented while Au (1994) found that even 4-year-olds occasionally maintain material identity after being ground into powder. One can hypothesize that this variability among younger children is due to individual differences in having achieved the notion of underlying constituent. It may also be due to other strategies, such as using similarity between large chunks and powders for some materials or relying on an essentialist bias. Both may allow some children witnessing the transformation and focusing on its history to reason “it was iron before, you just ground it up, so it is still iron.”

There is also evidence that children improve in their understandings that there can be pieces of matter too small to see with the naked eye, that is, that matter can exist even though one cannot see it or touch it. Piaget and Inhelder (1974) originally investigated young children’s understanding that dissolved sugar continues to exist. Prior to ages 7 or 8, children frequently denied that the sugar was still there whereas older children were more aware that there were still little pieces of sugar in the water. Several studies have also found that children’s understanding of contamination awareness begins to appear at this time (Fallon, Rozin, & Pliner, 1984; Rozin, 1990). In addition, Smith, Solomon, and Carey (2005) directly asked children whether there could be pieces of matter too small to see. The majority of 8-year-olds thought so, typically bringing up the case of germs or other tiny things that can only be seen with a microscope. Nonetheless, when pressed about whether or not one could repeatedly divide matter forever, the majority concluded that one could not because the pieces would eventually disappear.

This constituent view represents progress in conceptualizing matter and material kind but by itself it is limited: It is only an extension of children's initial idea that matter is detectable by the (unaided) senses and therefore is still anchored in perception. Thus it does not support conservation of matter without at least some actual or potential perceptual evidence (e.g., taste of sugar; visible with a microscope). Even older students often fail stricter tests for conservation—they believe that if one repeatedly cut the Styrofoam into smaller and smaller pieces, the pieces would disappear (e.g., Smith, in press; Smith et al., 1997) or fail to maintain conservation of matter across certain phase changes such as boiling, in which matter seems to disappear (Johnson, 1998b; Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993). For similar reasons, this view supports only a limited commitment to conservation of material kind across physical transformations. Transformations that preserve many perceptual properties (e.g., turning a chunk of iron into powder, dissolving sugar, and melting chocolate) may be more easily understood correctly than those that do not (melting wax). Finally, this view by itself does not support conceptualizing gases as material because, being based on perception and imagined mental division, it is "unidirectional": Starting with a chunk, one mentally divides it into little pieces, first really and then potentially visible. But, in children's experience, gases don't start as perceptible chunks; the decomposition schema is constrained by children's ontology and applies to what is conceived of as material to start with.

The relations of weight to matter and material kind. The Piagetian conservation literature suggests that during the elementary school years children markedly improve their understanding that weight and volume are conserved when objects get divided into smaller chunks or reshaped. The fact that conservation of matter (in the limited sense discussed previously) emerges prior to conservation of weight and volume (7-8 vs. 9-10 and 12-13 respectively) argues that the former does not depend on the latter, consistent with our findings that very few children use having weight as a criterion for being material.

Conservation of weight in Piaget's tasks, like conservation of amount of matter, is probably reached by reasoning that more stuff is heavier and less stuff is less heavy so weight stays the same if nothing is added or removed, and should not be interpreted in the scientific sense. There may be several reasons that conservation of weight lags behind conservation of matter. For many elementary school children, the core of the concept of weight is still felt weight, so that direct experience with adding and subtracting stuff may not provide (strong) support for their effect on weight; moreover, shape transformations do affect felt weight. It is likely that experience with measuring weight with balance scales is building up an objective aspect to the concept of weight (which may become central for some children and remain peripheral for others). This experience could be enough to link weight to amount of stuff and establish conservation of weight in the restricted sense—adding stuff on one side of the balance scale makes it tip, removing some makes it go up, not doing anything leaves it level. These experiences, as well as many in everyday life based on felt weight, also lead them to formulate a crude empirical generalizations—bigger things tend to be heavier; steel tends to be heavy, plastic tends to be light (Smith et al., 1985).

But this does not mean children have formulated the general principle that weight is a property of all matter nor that they have differentiated weight from density. Many children this age and even much older (8th grade) still think that a small *visible* piece of Styrofoam and that small enough pieces of any material weigh nothing at all (Carey, 1991; Smith et al., 2005, Smith, in press). Moreover, children's justifications fail to indicate that they have formed a general belief that all matter has weight, either in weight conservation tasks or in matter sorting tasks discussed previously. And, for the majority of those children, the relation between weight and material kind is based on a qualitative "heavy for size" concept not clearly differentiated from "heavy." These limitations are directly related to the enduring perceptual bases for the concepts of matter and weight: Felt weight does not support the differentiation of weight and density nor does it support the belief that tiny pieces have weight (a microscope may make invisible pieces visible but does not magnify weight).

Why are some conceptual changes harder than others? There is considerable evidence of enrichment of children's initial understanding of matter and material kinds during the elementary school years. As they get older, children certainly: acquire more knowledge about specific material kinds; are clearer that solids, liquids, and aggregates are matter; develop some generalizations about size, weight, matter, and material kinds; think more clearly of matter as an underlying constituent; and develop conservation of amount of matter and material kind across some physical transformations. These changes are achieved by the majority of students, the ease of their acquisition being consistent with the assumption that they involve elaborating on the (perceptually based) concepts they bring to elementary school, rather than restructuring them.

There is also evidence that new information that is not consistent with children's intuitive ideas creates incoherence and fragmentation. In the starting intuitive theory, matter being something that (a) one can see, feel, and touch; (b) disappears when cut into very tiny pieces; and (c) does not include gases and wax turning into water, form a (somewhat) coherent set of perceptually-based beliefs. In contrast, rote learning that gases are matter, mentally dividing a chunk of material into small pieces that are still matter but don't have clear properties, and being told that melted wax is still wax lead to less coherent beliefs because the link between matter and its properties loses its systematicity. Also, perceptual criteria lose their force, leaving children without a notion of what makes material kinds what they are, and of what matter is. Crude empirical generalizations also can lead to confusion: How can one account for small steel objects being sometimes heavier and sometimes lighter than bigger plastic objects? This unsatisfactory state of knowledge shows that traditional teaching does not provide the tools for students to create an alternative to their perceptually-based interpretive framework in which to make sense of received information and exploit generalizations they make on their own.

However, Smith and Carey find that some late elementary and middle school children do come to think that all matter must have some weight and that this belief is part of a new framework for thinking about matter and materials. This is often first evident in their correct responses to questions about the weight of tiny (and/or invisible) pieces of Styrofoam. They support these notions with general principles and modal statements—all matter weighs something, if it is there it must weigh something (Smith, in press)—that are much stronger kinds of justifications that those reported in the Piagetian weight conservation tasks (Elkind, 1961). Significantly, students who have made these changes have also made other changes in their understanding of matter. For example, they now refrain from talking about matter as something that one can see, feel, or touch and they espouse, in thought experiments, general beliefs that matter *must* continue to exist with repeated division; it can’t just disappear. They also differentiate between the weight of objects and the density of materials and have made progress in reconceptualizing weight and size as objective measurable properties (Smith, in press; Smith et al., 1997). Thus, the fact that these children have made coordinated changes in a variety of concepts (changing what is at the core vs. periphery, making conceptual differentiations and coalescences) argues that they have fundamentally changed their understandings of matter and materials and developed a productive new framework for thinking about them.

The proportion of students who give evidence of achieving this restructuring varies considerably among different student populations. For example, one study with middle-class children in a Montessori school found that the majority of 8- to 9-year-olds understood that small pieces of matter must weigh something when questioned about a small piece of Styrofoam or a grain of rice and clearly differentiated between weight and density in a simple paired comparisons task (Smith et al., 1985). However, this was not the case for 8- to 9- year-olds from another private school, where only a minority showed both understandings (Smith, 2003, unpublished data). Nor is it typically the case for even much older students. In one study of urban 7th graders, only 10% thought that small pieces of matter must weigh something and clearly differentiated weight and density (Smith, Grosslight, Davis, Under, & Snir, 1994). Among eighth graders in a suburban school, less than one-third of those in the main science track showed these understandings (Smith, 1993, unpublished data) prior to a teaching intervention, compared to two-thirds of students in the higher-math ability science track (Smith et al., 1997).

Why so much variability across populations and among students within the same population? Certainly this variability argues against viewing these achievements as "developmentally" inevitable. Broad factors are undoubtedly one source of variability—amount of content science knowledge being taught, quality of mathematical education, and individual students' academic level among them. We suspect, however, that more specific factors are involved. In keeping with our view that restructuring is not simply the result of a gradual (bottom-up) process that depends upon making enough piecemeal changes to one's initial ideas but also involves top-down processes (e.g., thought experiments, comparison, modeling) and a new epistemology, and therefore metacognitively guided learning, we believe that opportunities for metacognitive engagement, explicit model building, and discourse around these issues should be critical to promoting restructuring. Higher ability students may be more likely to create/seek these opportunities (as well as have more relevant prior knowledge), but classrooms may also vary enormously in the extent to which they provide these opportunities for all their students. (We will return to these issues in the later section that discusses the findings of explicit teaching studies.)

Take, for example, the concept of weight, which is central to a scientific understanding of matter. In order to construct an objective and extensive concept of weight, students need to make the ontological distinction between felt weight and weight as measured by a balance scale, to privilege the latter over the former, and to understand the properties of good measurement. Constructing measures of weight also involves cross-domain mapping between weight and number and upon reconceptualizing number as rational rather than counting number, another difficult conceptual change. Not surprisingly, there is evidence that these two conceptual changes occur at about the same time and appear to be mutually supportive (Smith et al., 2005).

Relating this additive (extensive) concept of weight to matter requires a mental model of matter with similar formal properties—that is, having the cognitive resources to divide mentally a chunk of matter into arbitrarily small pieces, focusing at the same time on each piece and on the whole, knowing that, even if cut infinitely small, the pieces cannot vanish or the whole would vanish. Bringing weight into this model results in understanding that, since the chunk has weight, each tiny piece of it has a tiny weight—all matter has weight, whether visible directly, or through a microscope, or too small to even imagine. This requires trusting the logic of a mental construct over perceptual evidence, a major epistemological leap of faith. It is likely that appreciating that the model provides a more stable and coherent view of the physical world helps one take the leap. For example, conservation of matter can be established by measuring weight and thus extended to melting, freezing, and dissolving transformations. And if one can imagine infinitely small pieces of a material, it is easier to believe that material kind is preserved even if radical perceptual changes take place.

Thus, as part of this conceptual restructuring, one sees an interesting shift in the relationships between ideas about matter and weight. Whereas early on children developed qualitative insights about matter that “pulled” deeper insights about weight (conservation of matter leads to conservation of weight when samples are cut or reshaped), further insights about matter may depend on their ability to measure weight and volume, which in turn depend upon using mathematical knowledge to inform physical understandings (Lehrer, Schauble, Strom, & Pligge, 2001).

The compositional model described above may contribute to the differentiation of density (which has its origin in “heavy-for-size” in the intuitive theory) from weight, as it makes it possible to contrast amount of matter and weight in a small portion of an object to the amount of matter and weight of the whole object. Constructing the concept of density also relies on new symbolic representations—graphs and (external) models (e.g., Lehrer et al., 2001; Smith et al., 1997). Graphing weight as a function of volume for different material kinds strengthens the additive nature of weight and supports the conceptualization of density, its differentiation from weight, and the mathematical relation between density, weight, and volume. By becoming an inherent characteristic of material kind,[3] density makes material kind a more abstract concept, integrates it more closely with matter (different materials have different densities because the matter of which they are constituted is distributed more sparsely), and strengthens the belief that all matter has weight (the reason that Styrofoam feels like nothing is not that it has no weight but that its density is very low). But this concept-building requires understanding that visual representations are tools for investigating and explaining phenomena, a form of hypothetico-deductive thinking that is not part of many students' epistemology.

The material nature of gases is still a challenge even for students who have the mathematical, cognitive, and metacognitive resources to restructure their concept of matter, although they now have a means for investigating the issue. Experiments showing that gases have weight are relevant to students who believe that matter has weight; a mental model of solids and liquids as constituted of tiny pieces might lend itself to a crude gas model, in which those tiny pieces are far apart. However, the atomic-molecular theory will make boiling, evaporation (as well as melting and freezing), and the nature of gases much more meaningful, giving solids, liquids, and gases a common ontology (they are all made of particles separated in space). It is also needed to account for melting and freezing, to understand the nature of chemical reactions and how they differ from physical transformations, and to grasp the difference between element, compound and mixture, all achievements that are beyond the scope of the macroscopic theory.

The Atomic-Molecular Model

The atomic-molecular theory is one of the most important contemporary scientific theories; as such it should be familiar to students graduating from high school. It offers parsimonious and elegant explanations of what makes materials different from each other, why and how they change phase, and why and how chemical reactions happen. Its basic tenets are few and simple. All matter is made up of atoms, which are far too small to see through an optical microscope. There is empty space (vacuum) between atoms. Each atom takes up space, has mass, and is in constant motion. All matter that we encounter on earth is made of less than 100 kinds of atoms. Each kind has distinctive properties, including mass and the way it combines with other atoms or molecules. Atoms can be joined (in different proportions) to form molecules or networks—a process that involves forming chemical bonds between atoms. Some substances (elements) are composed of just one kind of atom. Other substances (compounds) are composed of clusters of atoms bound together. Materials are mixtures of two or more (often many more) substances. Some materials are predominantly a single substance. Changes in matter include physical changes, in which molecules change arrangement and/or motion but remain intact, and chemical changes, in which atoms are rearranged (disconnected and reconnected) into new molecules but the atoms remain intact.

Irrespective of when the atomic-molecular theory is introduced into the curriculum, most 12th grade students display major misconceptions about the nature, behavior, and structural arrangements of atoms. They also have misconceptions about how the atomic-molecular model accounts for macroscopic properties and phenomena—for example, kinds of materials, weight, volume and density, latent and specific heat, phase changes, and chemical reactions. We will argue that this lack of understanding is not inevitable and is no reason to delay teaching the atomic-molecular theory.

Students working within traditional curricula face three major sources of difficulty in understanding and accepting the atomic-molecular theory. First, they do not have the epistemological knowledge necessary to reconcile everyday perceptual experience of material objects (solids and liquids appear continuous, the ground is solid, materials differ in color and hardness) with some of the basic tenets of the atomic-molecular theory (matter is discontinuous, atoms exist in a vacuum, atoms are neither hard nor soft and they are not colored). In particular, students know little about the nature of scientific models and of their relation to observed characteristics of objects and events. Another source of difficulty is not as widely recognized; it is that few students have the macroscopic conceptions of matter, weight, volume, and density necessary to support a sound understanding of the atomic-molecular theory. A third reason has to do with the way the atomic-molecular theory itself is taught: The information presented to students is not rich enough for them to make sense of the atomic-molecular model and the language and illustrations in textbooks are widely, if unwittingly, misleading.

In this section, we review some of the misconceptions students develop about atoms and molecules (when taught traditionally) and analyze the reasons those misconceptions develop. In later sections, we will consider the implications of these analyses for characterizing the epistemological, ontological, and macroscopic knowledge necessary to achieve a sound understanding of the basic atomic-molecular theory and for devising more effective instruction.

There is often more than one reason for a given misconception, and those reasons are often interlinked, both within levels of analysis (e.g., different beliefs about atoms support each other) and between levels of analysis (e.g., lack of epistemological understanding of models can cause misinterpretations of information about atoms). Some misconceptions are deep and well-entrenched; they tend to be those with interlinked reasons. Others seem more fleeting, probably created on the fly as students are interviewed rather than entrenched beliefs. We will note that not all misconceptions are undesirable, as some are an inherent part of the knowledge construction process. How desirable or undesirable a misconception is cannot be judged by how similar or distant it is from the scientists' conceptions but more on how it functions in supporting further growth and learning. Thus, it is important to distinguish among misconceptions that serve as valuable "stepping stones" for future learning (and might be inherent in the learning process) and those that do not and therefore should be prevented from developing.

Misconceptions about Atoms and Molecules and Some Hypotheses about Their Causes

Synthetic models of matter. Many students do not conceive of atoms as the basic constituents of matter but rather as something *in* matter. They view atoms as embedded in a material substrate (Andersson, 1990; Lee et al., 1993; Novick & Nussbaum, 1981), as if, by themselves, they were not sufficient to be the stuff from which things are made. This is an extremely powerful misconception that survives even through college chemistry instruction (Pozo & Crespo, 2005). Many reasons conspire to cause its entrenchment. One comes from students' epistemological commitment to naïve realism and their lack of sophistication in model-based reasoning. As a default position, they assume things are the way they appear. Matter looks continuous thus matter *is* inherently continuous (Harrison & Treagust, 2002; Nakhleh, Samarapungavan, & Saglam, 2005). Another comes from their macroscopic concepts of matter and materials. The Matter-in-Molecules model is a synthetic model (Vosniadou & Brewer, 1992); that is, it is a model resulting from the integration of school information into students' pre-existing intuitive theory (Ben-Zvi., Eylon, & Silberstein, 1986). A third is that textbook illustrations suggest and/or reinforce this model—a piece of substance is represented as a colored cube or sphere (with black boundaries), with small black spheres in it. So does language such as "Atoms *in* solids vibrate, while atoms *in* liquids…," "Molecules are less free to move *in* ice than *in* (liquid) water," "Bonds are the *glue* between atoms," and "Molecules *escape from the water* into the air when water boils." Direct observations may then be interpreted in light of such statements. For example, ice contains air pockets, as does water about to boil; some children think those are atoms (Ault, Novak, & Gowin, 1984).

Even students who are able to "suspend disbelief" to give the atomic-molecular model serious consideration find it impossible to do so on the basis of the information that is typically provided to them. Words used to describe atoms generate a wrong sense of scale about atoms and the gaps between them. For example, "microscopic" suggests that atoms can be seen with a light microscope; "particulate" suggests particles (e.g., of dust), and "nucleus," may lead to the "molecell" concept (Griffiths & Preston, 1992). Metaphysics is another obstacle—the existence of vacuum between atoms violates a deeply held metaphysical principle that vacuum does not exist in nature. The need to "fill the gaps" with stuff is all the more acute because most middle school students have no notion of the bonding forces holding molecules and atoms together, let alone of their magnitude compared to familiar forces (Johnson, 2000). This leaves students without recourse for understanding what holds matter together and prevents us from falling through the floor.

Another synthetic model, adopted by some students, illustrates similar reasons. Atoms are often introduced by asking students to imagine cutting a chunk of substance into smaller and smaller pieces. This generates a mental model of atoms as stacked cubes without space between them (Pfundt, 1981), an interpretation that fits the statement "matter is *made of* atoms" more closely than the Molecules-in-Matter model. It has the advantage of violating neither perceptual evidence nor students' epistemology and metaphysics, but it fails to represent the central idea that atoms are pre-existing constituents of matter, with specific size and mass.

These models of atoms are not scientific models of materials, not because they are wrong per se, but because they do not serve the *function* of scientific models. That is, they do not propose another level of description in order to explain the properties of materials. In the case of the Stacked-Cubes model, this is because atoms are not pre-existing units; they are simply the material itself. In the case of the Molecules-in-Matter models, it is because atoms are embedded in "stuff," thus begging the question of what the "stuff" is made of. Their use is largely unconstrained (e.g., Why can one not cut the stacked cubes into even smaller pieces? Why do atoms escape during boiling but not during melting?), and thus they are not revisable in a systematic way. They also do not contribute to further learning because they do not capture any (or even precursors) of the tenets of the atomic-molecular model upon which one could build. Thus, one of the goals of an effective curriculum should be to prevent their development, a point to which we will return later.

Misconceptions about the ontology of atoms and molecules. Underlying the alternative models students develop about atoms and molecules are fundamental misconceptions about what atoms and molecules are and what things are made of atoms and molecules (their ontology). Learning about atoms and molecules is difficult not only because it involves adding a new ontological level (atoms and molecules share few properties with macroscopic objects), but also because it involves making a fundamental distinction between atoms and molecules within this level (atoms are conserved across chemical transformations, whereas molecules can come in to existence and go out of existence). Creating new ontological levels will require serious theory-building, and in general students lack the epistemological sophistication to realize that is what they are doing. Instructional approaches compound the problem when they present the tenets of the atomic molecular theory as a set of facts rather than as an explanatory model.

Not surprisingly, students typically start by trying to map atoms and molecules onto existing ontological categories rather than creating new ones. Thus, students develop their own ideas of what atoms are and where they are found. Although some of those ideas are highly resistant to change, they do not form an alternative framework—they are context dependent, piecemeal, and not always coherent. Also, they exist in different combinations in different students. Nevertheless, several things unify them: They are developed within the ontological constraints of students' own macroscopic concepts; they are not developed to be explanatory, but out of a need to make sense of information that cannot be meaningful; and they are not useful stepping stones for further learning.

For many students, solid and liquids, which are visible and tangible, form the ontological category *matter,* while gases are something else, usually more closely related to heat and electricity than to matter. This ontological commitment at the macroscopic level, in interaction with students' selective attention to information presented to them about atoms, leads to misconceptions about the nature of atoms. If students formulate the belief "everything has atoms—solids, liquids, and gases," they are likely to think of atoms as nonmaterial, gas-like "specks" embedded in solids and liquids and floating in gases, for example. On the other hand, if they focus on "iron is made of atoms of iron, mercury is made of atoms of mercury, and air is made of atoms," they are likely to construct the (correct) belief that there are different kinds of atoms but to conclude (incorrectly) that some atoms are little pieces of matter (e.g., iron) while others are not (e.g., oxygen). Or, if they focus on "matter is made of atoms," they might conclude that atoms are found only in solids and liquids, which form the domain of their matter concept.

Students’ macroscopic concepts of weight and volume also affect their beliefs about what atoms are and where they are found. For many middle school students, weight and volume are still, essentially, properties of objects that can be felt or hefted, or seen respectively, so that very little pieces of matter don’t weigh anything or occupy space. If atoms don’t weigh anything, don’t “feel like anything,” and don’t occupy space because they are too small, they cannot be constitutive of matter, which one can touch and see. This would reinforce the need to embed atoms in “stuff.” On the other hand, given that gases are not matter, it might make sense that only gases, but not solids and liquids, are made of atoms.

Correlational studies support the link between holding alternative conceptions at the macroscopic level and having difficulties with understanding the atomic-molecular theory as an explanatory model and internalizing its core tenets. Snir, Smith, and Raz (2003) showed that students who were successful in understanding how atoms/molecules explained certain macroscopic phenomena also had sound macroscopic understandings of matter, weight, volume, and density. Lee et al. (1993) showed that macroscopic and atomic-molecular misconceptions coexist at equivalent levels in sixth graders regarding many issues (the material nature of gases, what happens in phase change, dissolving, etc.). Teaching that addresses both levels is much more successful than teaching that addresses just the atomic-molecular level.

Many students make some progress in high school toward viewing atoms as little pieces of matter that weigh something and have something to do with the properties of materials, mostly upon the introduction of the periodic table in their first chemistry course (Wiser, O’Connor, & Higgins, 1995). However, they do not understand that macroscopic properties and events are *emergent*. For example, fluidity has to do with atomic structure and molecular bonds, not with atoms being fluid; substances may differ while being made up of the same atoms (in different arrangements); and liquids taking the shape of their containers does not imply that atoms do. They think of atoms/molecules as little homogeneous parts of macroscopic objects to which they overextend macroscopic properties (i.e., hotness, squishiness, hardness, being solid or liquid, being static, etc.). This is one of the most robust misconceptions about atoms in the literature (Andersson, 1990; Ben-Zvi et al., 1986; Johnson, 1998a, 2000).

Failing to differentiate the properties of atoms and macroscopic properties of materials deeply affects students' understanding of physical transformations. If atoms and molecules have all the properties of macroscopic matter, then they themselves change during phase changes. For example, many students say that molecules change size and weight upon heating and during phase change, liquefy during melting and dissolution, and disappear when liquids boil (Griffiths & Preston, 1992; Lee et al., 1993).

Undoubtedly, a naïve realist epistemology and a lack of knowledge about models are at the root of the overextension of macroscopic properties to atoms and molecules: If at a macroscopic level materials have certain properties, then atoms themselves are that way, too. However, this is not the only cause of overextension. As in the case of the structure of matter, students are not given content information about atomic and molecular bonds that would help them understand how, for example, materials can be flexible without being made of flexible atoms or melt without individual atoms becoming liquid.

The relation between heat and atoms presents the same problems, with an added ontological challenge. In physics, heat is the energy exchanged by objects at different temperatures. For students, it is a (usually immaterial) entity, existing *in* matter, with the intrinsic property of hotness. This concept offers no explanation for why substances melt and boil when heat is added to them. Moreover, after being taught that “everything in the world” is made of atoms, many students infer that there are heat atoms and cold atoms, or that atoms are hot and cold (Wiser, 1986). For students to understand and accept the scientific account of heating and phase change at the atomic-molecular level, they need to be given an account for object-sense interaction so that they understand how hotness can arise from atomic motion. Wiser and Amin (2001) have found that a simple explanation of how atoms interact with thermal skin detectors to cause brain signals interpreted as hotness helped students to make an ontological distinction between heat (as objective molecular energy) and hotness (as a perceptual property in the perceiver’s mind).

Color presents still greater pedagogical challenges because it is a purely perceptual property. Atoms are neither flexible nor blue, but groups of atoms are flexible, whereas groups of atoms are not blue. Properties such as fluidity, hardness, and flexibility are perceptual properties but they are also inherent physical properties of materials, which have objective manifestations in the interactions between objects. Moreover, students can use their macroscopic intuitions to grasp that less tightly bound atoms or molecules imply a more flexible material and underlie melting. The conceptual change involved in understanding that those properties are properties of groups of atoms, not of individual atoms, is not as radical as for hotness and color. Color is particularly difficult because the physical phenomenon of light reflection and absorption by groups of atoms and the perceptual mechanism involved in color perception are both complex.

Understanding what a chemical transformation is and how it differs from a physical transformation is difficult to achieve for the reasons just reviewed. At the core of understanding the nature of chemical reactions and accounting for the changes in appearance they create is grasping their emergent nature, differentiating and relating perceptual properties and physical ones, and having a concept of bonds. Atoms are conserved, but they are rearranged into different molecules, and it is the new spatial arrangement that underlie changes in color, density, texture, and so on. Without that knowledge, students infer that what is happening at the macroscopic level is happening to the atoms and molecules themselves—for example, when iron rusts, atoms of iron get covered with rust.

Moreover, understanding the difference between physical and chemical transformations requires the distinction between atom and molecule and between intra- and intermolecular forces. In phase change, molecules are conserved and heat affects the strength of the intermolecular forces, while in chemical reactions, molecules are not conserved but atoms are. Most students do not make these distinctions and will often believe, for example, that water molecules break down into hydrogen and oxygen when water boils (Osborne & Freyberg, 1985). A perhaps subtler consequence of students' epistemological shortcomings and lack of information about atomic and molecular forces is their difficulty in understanding chemical reactions as dynamic interactions between molecules. In keeping with a "mixing" view of chemical reactions at the macroscopic level, some students describe molecules produced in chemical reaction as concatenating without affecting each other (Pozo, 2001)

Summary of the epistemological, ontological, and macrosocopic knowledge that (would) make the atomic-molecular theory meaningful. Mastering the atomic-molecular theory requires epistemological, ontological, and macroscopic knowledge that, for many students, is not in place by the time the theory is presented to them—nor is it acquired as they are studying it. Epistemologically, students need to understand the nature and function of scientific models—that their elements are different from the entities they account for, their value is in their explanatory power, they represent hypotheses and are revisable. Students also need to realize the ontological distinction between perceptual and physical properties and to understand how they are linked, rather than treat the perceptual properties of matter from a naïve realist point of view. This more advanced epistemology and new ontological distinction are the basis on which an understanding of emergent properties can be built: Atoms invisible to the naked eye can form visible matter with physical and perceptual properties they themselves do not have.

The relation between the macroscopic theory of matter and the atomic-molecular model is bidirectional—for the latter to account for the former, they have to be understood each in their own right and in compatible ways. This does not mean that the atomic-molecular theory cannot be taught before students have a complete scientific theory of matter at the macroscopic level; in fact, we will argue it should. Obviously, some macroscopic understanding of matter must be in place for the atomic model to be a model of matter. But some aspects of the macroscopic theory (e.g., the idea of chemical reaction, substance, compound and mixtures, as well as a full appreciation of the material nature of gases) take their meanings from the atomic-molecular model and thus are better taught after students have had some exposure to it. (This claim is not uncontroversial and will be developed below.) How to orchestrate macroscopic and nanoscopic teachings to create a learning progression between those two points is a crucial issue that has received little attention. Should students have a rich and solid macroscopic understanding of matter, measurement, and models before atoms are introduced? Or would an early curriculum about atoms contribute to this macroscopic and epistemological understanding, and perhaps avoid (some) prevalent misconceptions about atoms and molecules? These issues can only be explored and settled on the basis of long-term teaching studies. We suspect that multiple learning trajectories are possible but surmise that they will share several important features: The elementary curriculum will have a strong emphasis on developing the macroscopic concepts of matter, weight, volume and density as they pertain to solids and liquids; on a progressively finer grained compositional view of matter; and on measurement, model building, and the distinction between perceptual and objective properties. The idea that matter has structure might be introduced early or late in the curriculum but in a manner consistent with students' macroscopic concepts at the time. It will lead to (if introduced early) or consist of (if introduced later) a particulate[4] model that will include the concepts of unchangeable particles, existing in the vacuum and held by bonds of varying strength. This model will be the basis for the atomic-molecular theory, which itself will be the basis on which to study chemical reactions, substances, compounds and mixtures. Students will be actively involved in developing and/or assessing compositional and particulate models in explanatory contexts (e.g., differences between material kinds and phase changes).

In the last two sections of this paper, we review some teaching interventions that support our view and propose a learning progression that incorporates the features just discussed.

What Conceptual Changes Should be Worked on in Elementary School?

In the previous sections we have shown that the scientific theory of matter, both at the macroscopic and atomic level, is far removed from everyday experience and challenges everyday epistemological and ontological assumptions and we have highlighted the many kinds of conceptual changes needed to develop it. In this section, we review both conceptual and empirical arguments for the importance of developing *a robust and mutually supportive set* of macroscopic, ontological, and epistemological understandings in elementary school to provide an appropriate foundation for learning about the atomic molecular theory in later years.

Overview of Conceptual Changes in Restructuring Macroscopic Concepts and Why They are Important

Table 1 provides an overview of some of the important understandings for students to develop during the elementary school years and the kinds of conceptual changes they involve. These changes include: (a) extending and restructuring their macroscopic concepts of weight, size, material kind, and matter so that they are now inter-related and based on objective (measurable) properties and support an understanding of conservation of matter, weight, and material kind across a range of transformations; (b) developing their epistemological understanding of the role of measurement, models, and argument in theory building; and (c) changing their ontological commitments through coalescing solids, liquids, and gases as forms of matter and distinguishing objective from sensory-based properties.

Perception-based concepts do not provide a framework that allows developing either macroscopic or atomic understanding of matter. If matter is something that can be seen, felt, and touched, and if felt weight is central to the concept of weight, then gases are immaterial and weightless and belong to a different ontological kind from solids and liquids. Moreover, the notion that atoms, which are too small to see and feel, are the constituents of matter, is ultimately incoherent. Similarly, such perception-based concepts of weight and matter do not permit students to differentiate weight and density or to understand the conservation of weight across decomposition and phase change. Further, if models are judged by their match with surface appearance rather than explanatory force or ability to represent key relations, then neither the decompositional models of measurement (in which one subdivides continuous magnitudes into unseen identical units) and of matter (in which one subdivides a sample into unseen identical, infinitely small pieces) nor the atomic-molecular model of matter are prima facie good models of objects and materials.

In contrast, if students' understanding of measurement and models allow them to conceive of weight and volume as objective, extensive properties and to visualize decomposing matter into tiny pieces that continue to exist even if they are not directly detectable by the senses, then their models of weight and volume can be linked to a compositional model of matter, producing the understanding that any piece of matter, however small, has weight and occupies space. These students also have the basis for coordinating weight and volume in a concept of density for determining that gases are material and for investigating conservation of matter across a variety of transformations. If they know that matter takes up space and has weight, they can be puzzled by phenomena where weight is conserved but volume changes (e.g., thermal expansion, phase changes). This helps motivate the idea that matter is composed of discrete particles separated by empty space, paving the way for the atomic model. With sound macroscopic understandings of matter, weight, and material kind, they have firm enough expectations to be puzzled by phenomena that can motivate distinguishing chemical from physical change. For example, why under some conditions can materials be combined in any proportion and produce a material with physical properties that are the averages of the properties of its components, while in other conditions materials combine in fixed proportions and produce materials with novel properties?

Evidence that Elementary School Students Can Develop Relevant Macroscopic and Epistemological Understandings

For a long time it had been assumed that developing these macroscopic and epistemological understandings was out of reach of elementary school students because they required abstract "formal operational thought." Elementary school children were assumed to be concrete thinkers, so that their instruction should be primarily piecemeal and factual, laying the observation base for later theorizing in the upper grades. Hence, measurement was taught as a set of procedures to be learned and mastered, not tied to theory development or the solving of important intellectual puzzles. Similarly, students were simply *told* that solids, liquids, and gases were types of matter and that all matter was composed of atoms rather than engaged in active theorizing about the nature of matter and materials that would allow these statements to make sense.

There is now, however, overwhelming evidence that traditional elementary and middle school science instruction (with its emphasis either on cookbook activities, unguided discovery, or didactic instruction) is a resounding failure in building a base for later learning. For example, few middle school students think matter has weight and volume (Smith, in press; Stavy, 1991), know how to measure weight and volume (Smith, in press), and differentiate weight and density (Hewson, 1986; Smith et al., 1997). In addition, exposed to science curricula that treat knowledge as unproblematic facts, few students have any appreciation of the coherent nature of scientific theories or of the role of ideas, models, and symbolization, and cycles of hypothesis testing in their creation (Carey, Evans, Honda, Jay, & Unger, 1989; Driver, Leach, Millar, & Scott, 1996; Grosslight, Unger, Jay, & Smith, 1991). The fact that students often make little or no progress in developing these understandings with increasing age demonstrates that these understandings do not simply magically appear with unaided “development.” Hence, the “let's wait until they are developmentally ready” strategy of science teaching is fundamentally flawed.

We now know these approaches fail because they both over- and underestimate the capacities of elementary school students. They *overestimate* the extent to which students’ initial concepts and model-building efforts match those of scientists, and thus the extent to which students can internalize the statements and procedures being taught without being given experiences that enable them to develop a framework in which they make sense. Developing this framework is based on the capacity to engage in symbolization, model-based reasoning, and argumentation (in socially supported instructional contexts) right from the start, a capacity that is severely *underestimated* and therefore ignored in elementary school curricula.

Acher and Arca's work suggests that very young students are capable of developing initial models of the structure of matter when such models are scaffolded by their teacher (Acher & Arca, 2006; Acher, Arca, & Sanmarti, 2007). In their studies, 4- to 9-year-olds model materials and their physical transformations via drawing but also role playing, verbal descriptions, and gestures. The guiding themes of those activities are structure, (large quantity of) discrete parts, bonds between the parts, and the idea that the strength of a structure depends on its bonds. Children start by representing the visible structure of different materials, then are asked to imagine and represent smaller grain structures, and end up modeling phase as changes in the strength of bonds. This learning progression allows the construction of progressively more complex models of materials, drawing on children's ability to impose an imaginary discrete structure on a visible continuum as well as their ability to think of structures systematically by thinking of parts and relations among parts. Although Arca and Acher provide evidence of young children's abilities to model and reflect on unseen entities, the curriculum as a whole has not been implemented with a single cohort, nor has it submitted to systematic assessment. It also raises a large number of questions about its long-term consequences that have not yet been explored: for example, how it interacts with the development of other concepts (e.g., weight and density), what epistemological lessons it teaches, and whether it prevents the development of misconceptions about atoms later on (when concepts of atoms and molecules are explicitly taught).

A number of researchers have taken on the challenge of trying to improve elementary or middle school students' macroscopic understandings of matter, weight, volume, or density by designing innovative curriculum units (Lehrer et al., 2001; Raghavan & Glaser, 1995, Smith, Snir, & Grosslight, 1992; Smith et al., 1997). Although the focus and methods of these curriculum units varies, none relies on simple didactic instruction or unguided inquiry. Rather, a common feature is the curriculum developers' awareness of students' initial views and their sustained attempts to engage students in constructing new representations or models that help them investigate and account for key phenomena. The fact that students make much more progress with these innovative curriculum materials than traditional ones is an important piece of evidence that students' conceptual difficulties can be addressed with more appropriate science instruction.

For example, Smith and her colleagues have designed curriculum units that engage students with thinking about the properties of matter and with building macroscopic models that visually depict the inter-relation among volume, mass, and density of materials (Smith et al., 1997). These units work simultaneously on several fronts: (a) raising explicit questions about the nature and purpose of model-building (especially trying to highlight the importance of a model showing relationships among variables rather than just depicting how something looks); (b) engaging students in reasoning about properties that all matter share and with thought experiments that challenge them to consider what happens in extreme cases (such as when something is divided into smaller and smaller pieces that get vanishingly small) to foster a coherent and consistent way of reasoning about matter across a wide range of situations; (c) developing students' ability to quantify and measure weight and volume so as to clarify the extensive nature of both physical quantities; and (d) having students construct visual models with distinct yet integrated representations of volume, weight, and density that allow them not only to differentiate among these quantities but also to realize that density is a characteristic property of materials.

This model-based conceptual change approach has been consistently effective in helping 7th and 8th grade students from a variety of backgrounds (suburban, inner city) develop more abstract conceptions of matter (matter has mass and takes up space, gases are material); reconceptualize weight as an objective, quantifiable property of matter; and make progress in differentiating weight and density as fundamentally different kinds of magnitudes (Smith, in press; Smith et al., 1994, 1997). It has been found to be much more effective in bringing about conceptual change than the standard Introductory Physical Science curriculum that addresses these topics (Smith et al., 1997).

An alternative, more mathematically-based approach to helping students construct a concept of density was reported by Lehrer, Schauble, Strom, and Pligge (2001).[5] Their intervention with 5th graders in modeling material kind was part of a much larger sustained multi-year collaboration with participating teachers in which they worked to “reorient mathematics and science instruction around the construction, evaluation, and revision of models” (p. 39). In earlier grades, they had worked on a variety of “big ideas,” including developing a theory of measure, as first applied to measuring length and then later area (Lehrer, Jaslow, & Curtis, 2003). In this earlier work students were encouraged to create their own nonstandard units and work through features of a “good” measurement before moving on to more standard units. In the process, they learned important ideas about units (e.g., the idea of iteration, identical unit, covering the measurement space, partitioning units to form fractional units) and about scale (e.g., the importance of a zero-point, the need for appropriate precision, and inherent limitations of measurement in accuracy.) In their semester-long work in 5th grade, students first learned to extend these ideas of measure to tackle the problem of developing measures of volume. They next worked with families of magnified rectangles to develop a mathematical expression for “same, but bigger”: straight line graphs through the origin showing the ratios of the two sides. Finally, students explored a variety of objects of different volume and material, ultimately testing their conjecture that there might be “families of materials.” As part of these investigations, students built on their previous understandings of the measure of volume and the mathematics of similarity. They also constructed a measure of weight, made weight and volume measurements of different size samples of different materials, and wrestled with problems of the reliability and accuracy of measurements (especially when they had to use water displacement methods to estimate the volumes of irregular solids). Finally, they plotted their data about the weight and volume of different objects on a coordinate graph. Their prior work with graphing families of similar rectangles led them to expect that each family of materials might be represented with a line of different slope; when their data points for objects made of the same material did not fall exactly on one line, they discussed the epistemological issue of why this might be and even considered which line would be best to draw through the obtained data points.

Significantly, these sustained investigations using graphical, algebraic, and tabular representations led these 5th grade students to the conclusion that materials varied in their weight/size ratios, that is, density. Further, they were able to use these insights to make and test novel predictions. This is particularly noteworthy since Rowell and Dawson (1983) had earlier shown that the ability to use straight-line graphical relations to infer the constancy of density eluded most 9th grade students. Clearly, elementary school children have a greater capacity for mathematical abstraction than is typically acknowledged or encouraged with standard math and science instruction. Further, using mathematical models is an important abstraction tool that aids in the development of science concepts like density.

These cases nicely illustrate some general principles of how conceptual change occurs. Conceptual change occurs in the context of multiple (iterative) cycles of model construction, testing, and revision, which involves both processes of conceptual elaboration and more major restructuring. Although model construction and testing is always constrained by students' initial conceptual and epistemological understandings, students can be led to use conceptual resources and symbolic tools from inside and outside a given domain to represent new organizing relationships if scaffolding is provided by instructional contexts. More specifically, the development of young children's *mathematical* insights and reasoning may play a much more powerful role in enabling the conceptual restructuring of children's physical concepts of matter, weight, volume, and density than many conceptual change researchers have realized.

Evidence that Developing these Understandings Leverages Later Change

Within each of these curricula, there are iterative cycles of model-building, with new insights building off prior ones and leveraging later change. But what is the evidence that this macroscopic and epistemological teaching leverages better understanding of the particulate theory of matter itself? Although there is not yet as much direct empirical evidence on this point, two findings are provocative and indicate that this issue merits further investigation.

First, there is direct evidence that developing a macroscopic understanding of matter (as having weight and taking up space) along with understanding weight and volume as objective measurable properties enables students to come to see gases as material (Smith, in press; Smith et al., 1997). Given that exploring the behavior of gases is commonly used in developing a particulate theory (see next section, and the work of Nussbaum, 1997), it is critical that students first conceptualize gases as material.

Second, developing an explicit belief that matter has weight and takes up space and differentiating weight and density sets the stage for students to be deeply puzzled by a variety of phenomena in which weight is conserved but volume changes. For example, how can heating a brass ball change its volume but not its weight? How is it possible that when water and alcohol are mixed, the volume of the mixture is less than the sum of the volumes of water and alcohol, although weight is conserved? These phenomena challenge students' belief that matter is fundamentally continuous and thus can be used to introduce the idea that matter is particulate. Significantly, research indicates that 5th and 6th grade students who have developed a sound macroscopic understanding of matter, weight, volume, and density were more likely to find these phenomena puzzling than those who have not. They were also more likely to evaluate models based on their capacity to explain phenomena rather than resemble them and hence are more likely to find particulate explanations of these phenomena compelling (Snir et al., 2003).

Further, in a teaching study with 7th graders in which these phenomena were used to introduce the idea that matter is particulate, a strong relationship was found between students' long-term internalization of the assumptions of the particulate model, their macroscopic understanding of matter and physical quantities, and their epistemological understanding of the particulate theory as an explanatory model. Students who remembered and used the basic tenets of the atomic-molecular theory six months later to provide explanations of both taught and novel phenomena were those who had a sound macroscopic understanding of matter and regarded it as a good explanatory model (Snir et al., 2003).

When and How Should the Atomic-Molecular Theory Be Taught?

Overview of Conceptual Changes Involved in Learning about Atoms, Molecules, and Chemical Reactions: Ontological and Epistemological Challenges

Mastering the atomic-molecular theory involves developing a large network of related concepts and beliefs that pose closely intertwined ontological and epistemological challenges. It rests on a sound macroscopic foundation, which it deepens with its new nanoscopic level. At the same time, it is motivated by macroscopic phenomena that can only be understood superficially, if at all, without it. Thus, new concepts are being constructed simultaneously at the nanoscopic and macroscopic levels, requiring a solid understanding of model- building.

Atoms are strange “objects”: They are the sole constituents of matter without having most of its macroscopic properties, and those they have may be the most counterintuitive, given their size—volume, weight, and mass. Moreover, they have properties uniquely their own: They are held together by electro-magnetic forces, move at very high speed, and exist in the vacuum; there are only about 100 different ones, whereas the number of materials surrounding us is practically infinite; and they are never created or destroyed (in physical and chemical reactions).

To make sense of these ontologically counterintuitive entities, students need objective (rather than perceptually-based) concepts of matter, weight, and volume in order for atoms to be understood as the constituents of matter. Believing experimental evidence for the existence of atoms and molecules requires modeling abilities in addition to objective macroscopic concepts, since such evidence is indirect and derived from measurement of macroscopic events.[6] For example, taking the decrease in volume when alcohol and water are mixed as supporting a discontinuous model of matter requires a scientific understanding of weight and volume and the ability to evaluate competing models of matter in terms of how well they can account for these observations.

On the other hand, as we argue in the next section, some concepts such as substance, compound, mixture, and chemical reaction cannot be solely understood at the macroscopic level and thus require some prior understanding of atoms and molecules. But if students are to learn new concepts via modeling, that is, by relating atomic models to experimental observations, they need categories of macroscopic phenomena (e.g., phase change vs. chemical reaction) that will support their model-building. In other words, they have to construct atomic-molecular explanations for phenomena that initially have at best only shallow meaning at the macroscopic level. Thus, the epistemological knowledge required at this stage, although not fundamentally different from that involved in developing a scientific understanding of matter at the macroscopic level, is more crucial and more sophisticated. The disparity between observed phenomena and theoretical models is much greater and the interplay between macroscopic and nanoscopic accounts, more complex. Moreover, the thinking involved in understanding the relation between the properties of atoms and molecules and the macroscopic properties of material kinds and of physical and chemical transformations requires a major shift from the "process" type of causal reasoning students are familiar with to one that acknowledges emergent properties and constraint-based interactions (Chi & Roscoe, 2002)

The Value of Intermediate Models

It is premature to propose a detailed learning progression for these conceptual and epistemological changes for lack of enough (comparative) experimental evidence of how understanding unfolds under different conditions of instruction over long periods of time. Johnson (1998c) notes that students' conceptual development is usually assessed in the context of teaching studies, so that it is hard to disentangle “inevitable” conceptual evolution from the effects of specific teaching.[7] Our position is slightly different. Any conceptual change is the result of teaching, formal or informal, so that the issue is not to disentangle “inevitable” from curriculum-specific change but rather to compare the effects of different curricula. The goal is to determine effective orders in which to present different concepts, experiments, models, and epistemological teachings, so that, at each stage, new information can be assimilated into students’ existing framework to further their knowledge in a way suitable for tackling the next part of the curriculum. In the rest of this section, we apply those considerations to one specific issue—the merits, or lack thereof, of “intermediate” models of the structure of matter: Are students’ models scientific models? Are they useful stepping stones? Should some of them be taught explicitly?

Based on his extensive three-year longitudinal study of 7th to 9th grade students, in which students were introduced to ideas of substance versus mixture and chemical reaction versus phase change at the macroscopic level, and particulate explanations of these phenomena, Johnson (1998a) identified a series of models of matter held by students. We will consider the major ones here: Model X in which matter is continuous and particles are not mentioned; Model A (Particles-in-Matter model; particles do not constitute matter); Model B (a particulate model in which matter is made of spaced particles, and only of those particles, and in which the particles have all the macroscopic properties of a substance, including its state); and Model C (the particulate model taught to the students: a substance is made of particles, specific to the substances they constitute and held together by different strength attraction forces that account for the three states of matter). None of the students initially conceptualized matter as particulate and none progressed to the taught model directly. A little more than half progressed directly to

Model B (in which particles are either solid, liquid, or gas) and the majority of those then progressed to Model C (in which particles are the same in the three states). In contrast, of those who first developed a Particles-in-Matter model (Model A), less than half achieved a particulate model (B or C, in which particles constitute matter) by the end of the study. Only two of those learned the target model (Model C).

These results support our earlier claim that the Particles-in-Matter model (Model A) is not inevitable. There is also no evidence that it is a useful stepping stone, since students who did *not* develop it were far more likely to end up mastering the model being taught (Model C) and to do so more quickly. Johnson does not fully explore the reasons that some students develop Model A while others go directly to a particulate model (Model B.) We conjecture that students with more limited (perception-based) understandings of matter and epistemologies that privilege everyday observation over measurement and modeling may be the ones most vulnerable to develop these misconceptions when exposed to teaching about atoms. Consistent with the importance of epistemological understandings, Johnson mentions that Model A students did not refer to their model when explaining phenomena, nor did they integrate information received (e.g., forces) into it. The results also support our claim that forces between particles can (and should) be introduced early in instruction in order to make particulate explanations more coherent and understandable to students. Johnson notes that his students made widespread (and cogent) use of interparticular forces in their explanations of states and phase change. Whether Johnson’s curriculum was more effective than a traditional one is likely but cannot be decided without quantitative comparisons with a control group of students taught in a more traditional way.

As to Model B (in which particles are either solid, liquid, or gas-like), some researchers (Chomat, Larcher, & Meheut, 1988; Pozo & Gomez Crespo, 2005) argue that it has none of the epistemological characteristics of a scientific model. Most fundamentally, it is not hypothetico-deductive (and therefore not revisable) because it is the macroscopic appearance of objects that accounts for its particulate description (this is liquid therefore it is made of liquid particles), not the other way around (it is liquid because, at this temperature, its particles have weak bonds). We find it useful to distinguish between two questions—whether students' models have characteristics of scientific models and whether those models are useful stepping stones for the atomic-molecular model. Model B appears to be a stepping stone: In Johnson's study, the majority of the students who reached the target Model C did so via Model B. Moreover, the interview protocols suggest that envisioning phase-specific particles separated in space allowed students to adopt the idea of interparticular forces and different motions and to use those notions in their account of states of matter, while hanging on to the idea that particles are, literally, little pieces of macroscopic matter. At some point, some of them must have understood that different forces were enough to account for the different states and that state-specific particles were redundant, although finer-grained interviews would be needed to ascertain the process by which students move from Model B to Model C. Thus, Model B might not be scientific, but it is revisable "cognitively" in the sense that it scaffolds learning the (more scientific) particulate model.

With unchangeable, discretely spaced particles that characterize a specific material and that are held together by forces (strong in solids, less strong in liquids, very weak in gases), Model C represents an important part of the content of the atomic model and gives a parsimonious account of differences between materials, phase changes, and dissolving. Most importantly, it allows students to understand that (and why) gases are material and unifies the ontology of solids, liquids, and gases. Epistemologically, it embodies the distinction between elements of a model and the observable phenomena to be explained, and, more specifically, that the macroscopic properties of substances are explained by the structure of collections of particles, not by the properties of an individual one. It is revisable: In the context of chemical reactions, the notion of particle can be differentiated between molecule and atoms and the notion of interparticular forces between intra-and intermolecular forces that are part of a full-fledged atomic-molecular model. It is likely that while Model C students already know that particles are not modified in phase changes, and therefore differentiate to some extent the ontology of macroscopic matter and of particles, they still think of them as tiny solid pieces. Introducing the notion that molecules are composed of atoms and are created and destroyed in chemical reactions should make the idea of atoms as little pieces of macroscopic matter less plausible. Similarly, students who, while adopting Model B or C, believed there was “air” between the particles, might find it easier to reject this notion when heavy emphasis is placed on chemical bonds, which might make the idea of vacuum less “unbelievable.” We therefore agree with Johnson that Model C may be viewed as an intermediate model, scaffolding the transition to a more elaborate version of the atomic-molecular theory.

In a study with 9th graders Chomat, Larcher, and Meheut (1988) taught a particulate model very similar to Model C, but their emphasis was on explicit modeling and model revision. Their students were asked to build and evaluate progressively more sophisticated models to account for progressively more complicated phenomena. At the end of the intervention, the majority of students showed a solid understanding of the epistemological enterprise and significant gains in their application of the basic model to the different phenomena and macroscopic understanding (e.g., the conservation of mass during thermal dilation and phase change) (Between 75% and 95% of students answered different types of questions correctly.) These findings show that teaching Model C can help students develop nanoscopic, macroscopic, and epistemological knowledge consistent with the scientific view. It also supports Johnson's claim that introducing different aspects of the atomic-molecular model progressively, giving students experience with phenomena supported by each intermediate model, makes good pedagogical sense.

Other studies show that younger students can use discretely spaced particle models (similar to Model C) explanatorily, with appropriate instructional scaffolding and support. For example, Lee et al. (1993) found that over half of their 6th grade students could use a particulate model to explain conservation of mass and material kind across phase change, thermal expansion, and dissolving. Snir et al. (2003) found 5th through 7th grade students (with sound macroscopic understanding of matter) could use such models to explain the loss of volume without loss of mass, when alcohol is mixed with water, the expansion of a metal ball on heating, and why materials combine in fixed proportions in chemical reactions. Nussbaum (1997) has shown that 7th grade students can use these models to explain many aspects of the behavior of gases, including its compressibility.

In summary, we believe that teaching a particulate model like Johnson's Model C in the context of physical transformations and the nature of gases is a productive way to lead to the atomic-molecular model, especially if such teaching includes explicit epistemological instruction. It is a way to divide and conquer ontological and epistemological challenges: Those involved in learning Model C are less daunting than if the atomic-molecular model had to be learned "from scratch" (especially if Model B is developed spontaneously and acts as scaffold).

Those involved in moving from Model C to the atomic-molecular model itself are difficult, but build on, rather than undo, those already mastered. However, comparative studies involving other sequences need to be conducted to validate this hypothesis empirically.

When to Teach the Atomic-Molecular Model

Two main reasons have been advanced for delaying teaching the atomic-molecular theory until (late) high school. One is the complexity of conceptual changes needed to understand it; the other is that it should be motivated by extensive experience with macroscopic phenomena, most notably chemical reactions (Fensham, 1994). We believe this position is misguided for several reasons. First, with the proper elementary school curriculum, students entering middle school could have the macroscopic and epistemological knowledge necessary to develop an intermediate particulate model, which captures some of the tenets of the atomic-molecular theory and can serve as a stepping stone for further learning in high school. Moreover, many topics that are seen as central in elementary and middle school instruction (e.g., phase change and water cycle, the nature of gases, and what makes material kinds different from each other) remain superficially understood without the atomic-molecular theory and motivate learning it. Third, chemical reactions make little sense without the atomic-molecular theory and thus cannot motivate it; on the other hand, they can motivate revising an intermediate particulate model. We now consider those reasons in more detail.

Some proponents of the “delay teaching the atomic-molecular theory” view may be influenced by the Piagetian tradition and believe that the atomic-molecular model is beyond the reach of middle school students because it requires hypothetico-deductive thinking and the coordination of three levels of description—macroscopic, atomic-molecular, and symbolic. This mistakenly assumes that “developmental readiness” is independent from “instructional history” and underestimates young students' capacity for abstract thinking. We have offered experimental evidence in the previous sections that, with proper instruction, elementary school students can undergo conceptual changes and achieve a macroscopic understanding of matter consistent with the scientific view. Middle school students can achieve a productive understanding of a particulate model, which embodies some of the basic tenets of the atomic-molecular model. Moreover, there is ample evidence that even elementary school students can develop a sound epistemological understanding of modeling, measurement, and aspects of hypothetico-deductive reasoning (see, for example, Lehrer & Schauble, 2000).

Many educators worry about the meaningfulness of the atomic-molecular theory when it is first introduced (e.g., Millar, 1990; Stocklmayer & Gilbert, 2002,) and argue that it should be presented as answering questions (e.g., why is glass transparent) and explaining events relevant to students' everyday lives (e.g., cooking, medications), rather than more decontextualized laboratory experiments. As Hallden (1990) points out, scientific theories do not (easily) answer the questions students have in mind; everyday phenomena are often much harder to account for than carefully selected laboratory experiments. We agree that this is an important issue but do not see that teaching macroscopic chemistry first bears on it, for several reasons. Chemical reactions themselves are disconnected from everyday life; if students find them interesting, it is usually for their "magical" side, rather than because they raise important theoretical questions (DeVos & Verdonk, 1987; Harrison & Treagust, 2002). More importantly, we doubt that much can be understood about chemical reactions exclusively at the macroscopic level.

For example, the idea that the concepts of substance and element can emerge from patterns of chemical reactions at the macroscopic level, and later be used to give meaning to atoms and molecules (Johnstone, 1982), has little theoretical or experimental support. Although students initially make a distinction between “pure substances” and mixtures, the macroscopic criteria by which they make these distinctions are completely different from those used by chemists, as they rest more on perceptual appearance (pure substances look homogeneous, mixtures do not) and transformational history (pure substances are those found in nature, mixtures are a product of “mixing” things or artificial processes) rather than the macroscopic tests used by chemists (e.g., does it have a fixed boiling or melting point?). Johnson (2002) notes that the idea of pure substance made little sense to his students prior to being taught the atomic model, and, more importantly, that students who were told about “melting point test” did not think of using it to determine whether a chemical reaction has produced a new substance. They had no way of understanding *how* new substances would be produced in the first place. On the other hand, he found that learning about atoms and molecules greatly facilitated developing a concept of chemical substance as something whose identity is maintained across phase change, determined by its properties such as the temperature at which it melts and the manner in which it does so, and being part of chemical combinations and decompositions. In other words, it is not that atoms and molecules account for the concepts of substance, compound, mixture, and chemical change already in place, but rather that they allow students to construct those concepts. Moreover, chemical reactions cannot be understood without the knowledge that gases are material and therefore can react with solids and liquids; and, as we detail below, a particulate model is really needed to consolidate understanding that gases are material. Hence, this is an important case where learning about atoms and molecules is part of the solution, rather than part of the problem, and an important reason that it is important to develop some atomic-molecular understandings early.

A related pedagogical debate is about the context in which to introduce the atomic (or particulate) model—solids and liquids, or gases. Nussbaum (1985, 1997) and Fensham (1994) believe that the atomic model should be introduced in the context of gases because it is easier to believe that gases are made of tiny particles undetectable by the senses, in constant motion, and separated by a vacuum, than to believe the same thing about solids and liquids. However, Pozo & Gomez Crespo (2005) argue that students who adopt the atomic view for gases do so for the wrong epistemological and ontological reasons: They are actually overextending, by analogy, the perceptual properties of gases (which appear to move on their own and be "insubstantial") to atoms and then inferring that solids and liquids, which are substantial and don't move on their own, are not made of atoms (see also Knerl et al., 1998). Johnson (1998b) makes a similar point: it is not that students start with the notion that gases are matter (in the sense that solids are), accept that they are made of atoms, and then extend the atomic model to solids and liquids; rather, it is the atomic model itself that helps make sense of the idea that gases are material. Our own position is that it makes sense to start with a particulate model developed in the context of solids and liquids so that the model is clearly a model of *matter* (in both the student's and the scientist's sense) and then use the model in the context of evaporation and boiling to develop the material nature of gases. In support of this position, Snir et al. (2003) identified a variety of phenomena involving solids and liquids—for example, the loss of volume in the mixture of two (seemingly continuous) liquids, water and alcohol, or the expansion of a metal ball with heating—for which students found particulate explanations (and the idea of space between particles) especially compelling.

Conclusions

We have used research to establish students' conceptual states when they start learning about matter at the macroscopic level and when they start learning about the atomic-molecular model. We have also analyzed the conceptual difficulties posed by the atomic-molecular theory as it is traditionally taught. A variety of conceptual and epistemological changes are needed to bridge young children's initial understanding of matter and the atomic theory, most of them not facilitated by existing curricula. On the basis of those analyses, and a review of some innovative, successful teaching interventions, we have made the case for a learning progression in which knowledge about matter becomes progressively more scientific while remaining coherent. We assume that this learning progression will involve a number of intermediate constructions that will act as stepping stones but that many dead-ended misconceptions will be avoided.

In this learning progression, some tenets of the atomic-molecular model are in place relatively early (end of elementary school or beginning of middle school), in the rich but not full-fledged form of a particulate model and as part of a science curriculum which, from kindergarten on, imparts epistemological knowledge about measurement and models. The particulate model also allows students to develop a macroscopic understanding of matter consistent with the scientific view. Children working with this kind of curriculum would learn about matter in the context of solids and liquids first. Matter has weight and volume; it exists as different material kinds that differ in various ways, including density and melting point, and are conserved during melting and freezing. They would acquire a progressively finer-grained compositional model of matter, allowing them to think of (homogeneous) objects being constituted of a material kind all the way through, and supporting conservation of amount of matter and weight under certain transformations. They would then start exploring gases—for example, air, water vapor, sublimated iodine and oxygen involved in rusting—using perception and weight measurements as evidence for their material nature. Existing research does not allow us to specify when or in what form to first introduce a particulate model (e.g., more or less didactically; early or late in elementary school; directly in a "Model C-like" form or as a progression of models about the visible, then microscopic, then nanoscopic structure of matter and its transformations). Also left unspecified, although of crucial importance, are the timetable for and links between specific macroscopic, epistemological, and particulate teaching that will ensure that students have the macroscopic understanding and epistemological resources that make models of matter meaningful and explanatory. In any case, by the beginning of middle school, students would be familiar with the scale and the invariance of particles[8] across phase change, the effects of heating and cooling on the bonds between them, and giving particulate accounts of differences between materials (density, hardness, melting point), thermal expansion, dissolving, melting and freezing, and the mixing of specific materials. The model could then be extended to account for evaporation and boiling and to strengthen students' understanding of the material nature of gases. The ontological differences between macroscopic samples, molecules, and atoms as well as the difference between elements, compounds and mixtures, between physical and chemical reactions (atoms are rearranged in chemical reactions, inter- and intramolecular forces are different), would be explored later in high school, in the context of chemical reactions.

One of the themes running through this proposed learning progression would be understanding the compositional nature of matter both at the macroscopic and nanoscopic level, as it is a central to developing an understanding of its conservation and transformations. Envisioning an object as made of macroscopic "chunks" allows a first sense of conservation of amount of matter and weight in Piagetian tasks. Constructing a model of a sample as divisible into arbitrary small pieces supports conservation of amount of matter and weight and of material kind when a solid is ground, melted, or dissolved, giving it a broader scope and a deeper sense.

Particulate models do the same thing for boiling and evaporation, and they give meaning to gases being matter. Finally, the atomic-molecular model explains the conservation of amount of matter and weight across chemical transformations while accounting for why substances are not always conserved. Thus, modeling is at the heart of learning about matter throughout the curriculum making epistemological teaching part and parcel of it.

Clearly much research is needed to understand the ingredients of successful pedagogical approaches, including comparing the effectiveness of curricula targeting different learning trajectories. On the basis of the successful interventions we have reviewed, we predict that all successful curricula will integrate macroscopic, epistemological, and particulate teaching. They will also engage students in explaining phenomena and/or developing and assessing models to account for those phenomena. We also predict that, however successful the curriculum, it will involve students for multiple years, supporting Stavy’s (1991) and Johnson’s (1998) plea to dispense with the “quick tell.”

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Table 1

Overview of Key Conceptual Changes in Elementary School Years

Key Change	**General Description**
Changes in concept of material kind.	Developing understanding of material kind as a dense causal nexus used to explain some properties of objects. Moving from perception-based understanding of material kinds (and their properties) to having an understanding material kinds as fundamental constituents that maintain their identity across decomposition and phase change and that have objective and measurable characteristic properties (such as density, boiling points); beginning to sort out reliability of properties in identifying materials (e.g., melting and boiling points are more reliable than surface perceptual properties); using multiple criteria, including objective properties and transformation history to trace continuity and discontinuity of material kinds across various transformations.
Changes in concepts of physical quantities	Moving from perception-based understanding of physical quantities to more objective (and differentiated) set of concepts, grounded in measurement and inter-related in a theory of matter (e.g., all matter has weight and takes up space; the weight of an object is the additive sum of its parts and a function of the volume of the object and the density of the material it is made of); differentiating weight and density, and length, area, surface area, and volume; developing

	a sound epistemological understanding of the importance of measurable quantities in science, instead of relying on sense impressions; developing an explicit theory of measure (e.g., understanding attribute-unit relations, need for identical units, use of fractional units and zero point), ability to measure weight, volume; understanding measurement error and what makes a good measurement.
Changes in concept of matter.	Developing general concept of matter as causal nexus; moving from perception-based understanding of matter as something you can see, feel, and touch (that can include solids and liquids, but excludes small objects and gases) to understanding matter as fundamental constituent that has weight and volume (that can now include solids, liquids, and gases as forms of matter, and hence all of the same ontological kind); developing understanding that matter and weight are conserved across a wide variety of transformations, although volume and density can change.
Changes in concept of models	Moving from resemblance-based understanding of models as little pictures, replicas, or scale models to more abstract understanding of explanatory models that can be used as reasoning tools and that capture important relationships. Change involves making a distinction between explanation and thing explained; acknowledging emergent properties; explanatory force replaces looks like as criterion for evaluating models.

Footnotes

1. "Traditional instruction" is in contrast to the kind of innovative curricula that we review later in this chapter. These curricula often differ in approach, scope, and epistemological focus rather than content goals per se.

2. This is true only in a gravitational field. However, the more general statement—all matter has mass—would be far less meaningful to students, given that the concept of mass is a difficult and late achievement.

3. This is a case of stepping stone—density will need to be revised as depending on temperature and state.

4. "Particulate" refers to a model that does not make the distinction between atom and molecule. However, as mentioned earlier, we believe that the term "particulate" should not be used pedagogically, as it suggests wrong scale and ontology to students.

5. This approach was also successfully used with 3rd graders (Lehrer, Strom, & Confrey, 2002).

6. Advanced technology (Scanning Tunneling Microscope or STM; Scanning Electron Microscopy or SEM; Atomic Force Microscopy or AFM) allows scientists and students to construct visualizations of matter at the atomic scale and provides powerful evidence for the existence of atoms. Some researchers are beginning to explore its usefulness in the teaching of middle school students (Margel, Eylon, & Schertz, 2004). However, whether one can rightfully claim that the images provided by this technology show "atoms" rather than being evidence for

them is a complicated epistemological issue. Moreover, they do not provide evidence for other tenets of the theory, such as there being space between them not filled with matter, nor for the distinction between atomic and macroscopic properties.

7. "Inevitable" does not mean innately determined but rather the only way a concept can evolve given existing cognitive constraints and the kind of information typically received by students.

8. The meaning of "particle" should be explicitly distinguished from its everyday meaning, or particles should be called something else. See footnote 4.