Understanding the Particulate Nature of Matter

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Recent studies of students' conceptual knowledge of chemistry indicate that students do not understand some of the fundamental ideas that form the basis of the discipline. Misconceptions about physical and chemical changes on the three levels that chemists use to describe chemical phenomena are common. On the macroscopic level, Osborne and Cosgrove (*1*) in a study on the changes of states of water found that 25% of their sample of 17-year-old chemistry students thought that the bubbles in boiling water were made of air. Shepherd and Renner (*2*), who examined student's perceptions of the states of matter on the microscopic level, found none of the high school students in their sample had a sound understanding of the particulate nature of gases, liquids, and solids, and that only 43% had a partial understanding. This lack of understanding of the particulate nature of matter is confirmed by Novick and Nussbaum (*3*) who found that although misconceptions diminish with schooling, they still persist in university students. They found that among students in the university and in high school, 50% did not attribute the uniformity of particle distribution in gases to inherent particle motion, and over 60% did not picture space in a gaseous medium.

In addition to the prevalence of misconceptions on the macroscopic and microscopic levels, students do not understand the meaning of the symbols chemists use to represent the macroscopic and microscopic levels. Eylon, Ben-Zvi, and Silberstein (*4*) found that when given a chemical formula for a relatively simple molecule, 35% of the high school chemistry students were unable to represent it correctly using circles representing atoms. These students had an additive view of chemical reactions rather than an interactive one. Ben-zvi, Eylon, and Silberstein (*5*) also found that many students perceive a chemical formula as representing one unit of a substance rather than a collection of molecules. Of those that did perceive the formula as representing a number of particles in a solid, only two-thirds drew the particles in an ordered fashion.

Students are able to use formulas in equations and even balance equations correctly without understanding the meaning of the formula in terms of particles that the symbols represent. Yarroch (*6*) found that of the 14 high school students whom he interviewed, only half were able to represent the correct linkages of atoms in molecules. For example, in the equation, $N_2 + 3H_2 \rightarrow 2NH_3$, students do not differentiate between $3H_2$ as OO OO OO and OOOOOO.

This lack of understanding of the particulate nature of matter on the part of chemistry students may be related to their lack of formal operational development (*7–10*) or to their poor visualization ability (*11–13*). On the other hand it is more likely due to their lack of differentiation of concepts such as solids, liquids, gases, elements, compounds, substances, mixtures, solutions, etc., and to the lack of instruction in which these terms are related to the particulate nature of matter.

The ability to represent matter at the particulate level is important in explaining phenomena or chemical reactions, changes in state and the gas laws, stoichiometric relationships, and solution chemistry. It is fundamental to the nature of chemistry itself.

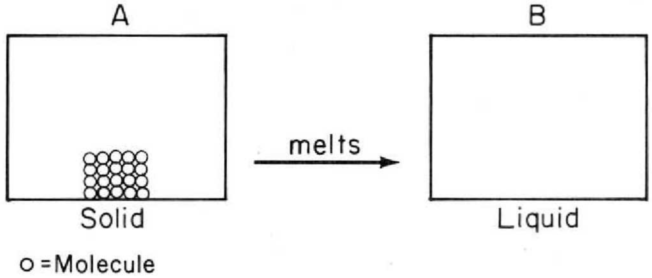
Instruction on the Particulate Nature of Matter

The age level at which people should be introduced to the particulate nature of matter is somewhat questionable. If elementary science texts are examined, atoms and molecules are depicted in even the primary grades. The Introductory Physical Science (IPS) text (*14*), a ninth-grade course devised in the late '60's, introduced the particulate nature of matter at the end of the year from an experimental viewpoint after students understood mass, volume, density, and other macroscopic properties of matter. This approach would appear to be more appropriate since children in elementary classrooms fail to distinguish between melting and dissolving, mass and volume, chemical and physical changes, liters and meters, etc. It would seem if children knew more about the "what" of chemical phenomena, they would have the basis to understand the "why" when it is presented at the secondary level.

However, it is a reality that the microscopic level is depicted in elementary science texts. This, coupled with the fact that elementary teachers would be familiar with the particulate nature of matter in order to make sense of every day phenomena that they encounter and teach to children, explains the inclusion of the topic as a part of a Basic Science Skills course at Indiana University. An additional reason for inclusion of the topic is to show students how theories and models are an outgrowth of the other science process skills of observation, inferring, predicting, hypothesizing, experimenting, etc.

Study of Preservice Teachers Views

In order to determine prospective elementary teachers views of the particulate nature of matter before instruction on the topic, a 14-item Nature of Matter Inventory was devised. The test showed pictures of matter with atoms and molecules depicted as circles of various sizes and shades. Students were asked to draw a new picture after a chemical or physical change occurred. In order to perform well on the test students would need to be able to distinguish elements, compounds, mixtures, substances, solutions, homogeneous matter, heterogeneous matter, solids, liquids, gases, and chemical and physical changes in terms of the particulate view of matter. An example of an item is shown in the figure. No clues were given to students on how the inventories would be scored.



Typical item on the Nature of Matter Inventory.

Correct Conceptions on the Nature of Matter Inventory According to Chemistry Background

Attribute	Chemistry (n = 54) $\bar{x}^a$	s.d.	No chemistry (n = 36) $\bar{x}$	s.d.	F	α
1. Conservation of particles	2.96	2.22	1.97	1.75	2.25	0.027
2. Particle proximity	10.91	2.30	9.92	2.32	1.99	0.049
3. Orderliness	6.67	2.01	6.63	1.84	0.80	0.427
4. Location in container	10.70	2.44	9.72	2.12	1.97	0.052
5. Constancy of size/shape	10.87	2.28	9.19	2.40	3.34	0.001
6. Discreteness	13.20	1.50	12.72	1.56	1.47	0.145
7. Chemical composition	9.22	1.98	7.92	2.27	2.89	0.005
8. Arrangement of products	9.65	1.94	8.44	2.04	2.82	0.006
9. Bonding	9.93	2.26	8.56	2.63	2.63	0.010

[a] maximum score = 14 for each attribute

In addition to the Nature of Matter Inventory, three other instruments were used in the study: a test to assess formal reasoning capability (*15*), a spatial visualization test (*16*), and a questionnaire on which they reported their chemistry and mathematics background. This information was used to determine whether there was a relationship between these factors and performance on the Nature of Matter Inventory.

Because it was desirable to study students' conceptualization of matter in a systematic manner, a sheet was devised to code the Nature of Matter Inventory. It contained guidelines for examining nine attributes that students should have considered in drawing their diagram. These were:

(1) *Conservation of particles.* Did the students have approximately the same number of particles in their diagrams as were in the original diagram?

(2) *Proximity of particles.* Were the particles close to one another for a solid or a liquid and spread out for a gas?

(3) *Orderliness of particle arrangement.* Were solids shown in an orderly fashion and gases shown as disordered?

(4) *Location of particles in container.* Were solids and liquids shown at the bottom of the container? Did liquids go to the sides of the container? Were gases evenly distributed throughout?

(5) *Constancy of particle size and shape.* As solids changed to liquids, etc., did the particles remain the same size and shape?

(6) *Particle discreteness.* Did students change from a particle model to one that is continuous by adding lines and other "fuzzies"?

(7) *Chemial composition.* Did particle attachments remain the same for physical changes but change for chemical changes?

(8) *Arrangement of products.* If a chemical change occurred, were the new products correct? Are particles of the same substance identical?

(9) *Bonding.* Are atoms attached to each other in molecules when they should be?

Since there were 14 items in all and each item was graded on nine attributes, the maximum score on the test was 126. Two chemistry educators coded the inventory. After practicing on several tests until agreement was reached in the scoring process, each graded the same five inventories independently. A check on these inventories showed agreement at the 95% level.

Data were analyzed according to whether the prospective elementary teacher had taken a course in chemistry (high school, college, or both). The table gives the mean scores for each of the nine attributes that were coded as well as F values and probability levels.

An examination of the table shows several striking results. First, conservation of particles and the orderliness of particles are attributes that students ignored in over 50% of the examples. Whether this is due to carelessness, which might very well be the case, or whether students did not realize that particles are conserved and are ordered in certain ways as solids, liquids, and gases is not known from this study. Second, although there is a statistical difference on most items favoring students who have had chemistry instruction, there are small differences in the means of most items for the two groups. This indicates that, although chemistry courses must touch upon the particulate nature of matter to some degree, instruction is insufficient to bring students to a high level of understanding on most attributes.

In order to determine the relative importance of students' formal operational capacity, their visualization skill, and the number of chemistry and mathematics courses they took to their ability to represent matter on the particulate level correctly, a regression equation was formulated from the data as follows:

$$\text{Score on Nature of Matter Inventory} = 1.97F + 3.85C + 0.45V - 0.32M + 59.09$$

where F = formal operation score from Tolt Test, C = chemistry courses taken, V = visualization score from Rotation Test, and M = mathematics courses taken.

Data analysis showed that 22.8% of the variance in the score on the Nature of Matter Inventory was accounted for by students' formal operation score, and an additional 4.0% by the chemistry courses taken. Students' visualization skill and the number of mathematics courses taken did not add to the variance. This small additional variance due to enrollment in a chemistry course corroborates the similar finding from the analysis using the F test.

An examination of the individual drawings done by students revealed that their conception of matter were frequently distorted. Some of the more common errors in addition to those immediately obvious from the table were as follows:

- the enlargement of atoms as they changed from liquids to gases rather than becoming farther apart,
- the addition of lines to show levels of liquids rather than letting the top of the particles indicate the surface boundaries,
- picturing gases in an orderly rather than disorderly fashion, and
- showing particles in intact groups rather than in smaller groups after a molecule has decomposed.

All of these misconceptions need to be remedied by instruction.

Significance for Chemistry Education

The results of the study have implications beyond the preparation of future elementary teachers. Sixty percent of the students enrolled in this Basic Science Skills course had a previous course in high school or college chemistry. Yet their conceptions of the particulate nature of matter are far from desirable. Some chemistry educators might argue that poor scores result because the pictures in the inventories are two-dimensional and particles exist in a three-dimensional world. This may be true. Textbooks, however, frequently show identical two-dimensional diagrams of atoms and molecules. Others may argue that students should have been given the criteria upon which their pictures would be judged, and, had this been done, they would have done better. Undoubtedly this is also true. But the point is this: when students are not given guidelines they forget about the conservation of particles and they do a poor job in representing matter and physical and chemical changes it undergoes.

On the other hand, if chemists completed the inventory, they might make the same mistakes that these students made due to lack of attentiveness to detail or by focusing on a different attribute. Although chemists might not conserve particles or might enlarge the individual atoms unwittingly they would not make errors in representing chemical and physical changes!

The information obtained from this study has serious implications for the teaching of chemistry. In the past few years there has been an increased interest of science education researchers on problem solving. Instructors of introductory courses know that many students do not understand how to solve problems and frequently resort to algorithmic solutions. In order to be a successful problem solver in chemistry, many factors are involved. Some of these have been summarized by Reif (*17, 18*). In order to solve a problem correctly, the concepts involved in the problems must be understood and must be recalled without prompting. After a preliminary description of the problem is made in terms of what is given and what is sought, the problem needs to be redescribed according to the problem solver's frame of reference. This is frequently done by sketching the physical phenomena involved in the problem. For example, in physics acceleration problems it is helpful to sketch first the physical situation and then the forces acting via the vectors. In chemistry it would appear that depicting the physical phenomena in terms of the particulate nature of matter would also be helpful. The following examples illustrate just a few of the cases in which the particulate nature of matter sketches might enhance problem solving.

Research (*19*) and experience have shown that many students disregard the fact that 22.4 L is the volume of 1 mol of an ideal gas at STP. Students not only disregard ideal gas but also STP. They apply the 22.4 L to solids and liquids as well. If students were required to make a sketch of 1 mol of an ideal gas at STP using particles and then to compare it to what is given in the problem, they may be better able to solve molar volume problems.

Avogadro's Hypothesis and Dalton's Law of Partial Pressures would be more meaningful if sketches were used in solving problems. At a recent science fair, a youngster mistakenly reported that the volume of oxygen produced in the decomposition of water was greater than the volume of hydrogen. The youngster gave a perfectly logical explanation that the oxygen gas would take up more space because its atoms with eight protons and eight electrons were larger than those of hydrogen with one proton and one electron! Disregard for space between gas molecules and the lack of understanding of formulas led to his misinterpretation.

Chemistry students find solution problems involving dilutions and additions of solute very difficult. How can these problems be solved successfully without picturing how the addition of the solute to the solvent causes the solute particles to become closer together and the solution more concentrated?

The findings from this study and other research about students' views of the particulate nature of matter are cause for concern. Even after the study of chemistry, students cannot distinguish between some of the fundamental concepts on which all of chemistry is based such as solids, liquids, and gases or elements, mixtures, and compounds in terms of the particle model. An increased emphasis on the particulate nature of matter in introductory chemistry courses, such as suggested by James and Nelson (*20*) and the careful representation of particles by chemists when they are used in instruction might bring about not only an increased ability to solve chemistry problems but it may also help to make chemistry more understandable by providing the framework underlying the discipline.

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