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Integrating Particulate Representations into AP Chemistry and Introductory Chemistry Courses

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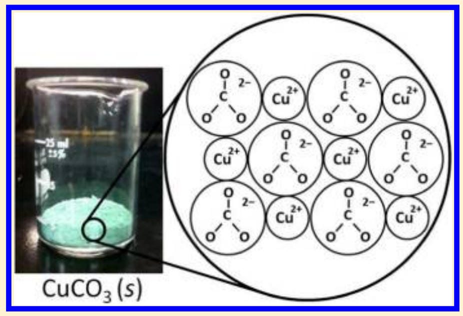
ABSTRACT: The College Board's recently revised curriculum for advanced placement (AP) chemistry places a strong emphasis on conceptual understanding, including representations of particle phenomena. This change in emphasis is informed by years of research showing that students could perform algorithmic calculations but not explain those calculations using particulate representations. This article provides a discussion of particulate representations in chemistry and specific examples of ways to introduce particulate representations to students and to integrate them throughout the AP chemistry or any introductory chemistry course. This contribution is part of a special issue on teaching introductory chemistry in the context of the advanced placement chemistry course redesign.



KEYWORDS: *High School/Introductory Chemistry, First Year Undergraduate/General, Curriculum, Internet/Web-Based Learning, Standards National/State*

INTRODUCTION

The College Board's redesigned Advanced Placement Chemistry curriculum,[1] which went into effect for the 2013−2014 school year, is based on the recommendations made by a 2002 report by the National Research Council.[2] That report was critical of many aspects of advanced high school science courses, including the curriculum, access to those courses, methods of instruction, and a failure to use research on how students learn. Regarding the focus of the AP curriculum, the report stated that "The primary goal of advanced study in any discipline should be for students to achieve a deep conceptual understanding of the discipline's content and unifying concepts" (pp 197−198). In doing so "[t]he College Board should abandon its practice of designing AP courses in most disciplines primarily to replicate typical introductory college courses" in their curriculum or pedagogy (p 203).

One of the central organizing principles of chemistry is that the macroscopic behavior we observe in the lab can be understood in terms of the behavior of the particles that compose all matter−atoms, molecules and ions. However, studies over the past 30 years have consistently shown that students who can solve standard quantitative problems often struggle to answer questions that depict particles and require students to reason about the number, distance, motion, and/or interactions between particles.[3−15] Students' inability to answer questions involving these particulate representations, as they are known, was first reported in a study[11] that asked students to balance reaction equations and then draw diagrams that described those reactions. While all 12 of the students in the study could balance the reaction equations, 7 of 12 students were unable to translate the symbols in their balanced reaction equations into meaningful drawings of atoms and molecules. A similar study of over 1300 students found a wide variety of errors in high school students asked to draw a representation showing atoms for the combustion of methane, including 22.9% of responses that were deemed "non-particulate".[13] In a series of studies,[5−7,14,15] student were much more likely to be able to solve standard gas law or stoichiometry problems than answer related questions involving particulate representations. These studies are alarming because they demonstrate that students can use a memorized algorithm to solve a problem without understanding the underlying chemical concept.

The new AP Chemistry curriculum takes this research into account by requiring students to demonstrate conceptual understanding of chemical phenomena at the particulate level in 13 separate learning objectives (LO) as well as the first of the interconnected Science Practices (SP) (Box 1). Most of these specifically state that students must be able to interpret or create particulate representations. Emphasizing particulate representations is a drastic change for AP Chemistry as can be seen by analyzing released AP Chemistry exam materials. No particulate representation question appeared on the standard form of the free response portion of the AP exam since at least 1999,[16] other than a single question on the 2013 exam requiring students to draw a picture of two molecules interacting based on hydrogen bonding. Of the last three released 70-item AP multiple choice exams (1999, 2002, and 2008), only two items with particulate representations appear, and both were on the most recently released exam.[17−19]

The shift in emphasis away from algorithmic computation and toward conceptual understanding including particulate representations is long overdue but may present challenges for many classroom teachers. Most of us currently teaching chemistry have limited examples of particulate representations

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Box 1. AP Chemistry Science Practices (SP) and Learning Objectives (LO) Containing References to Particulate Representations of Chemical Phenomena[1]

SP 1: The student can use representations and models to communicate scientific phenomena and solve scientific problems.
LO 1.17: The student is able to express the law of conservation of mass quantitatively and qualitatively using symbolic representations and particulate drawings.
LO 2.1: Students can predict properties of substances based on their chemical formulas, and provide explanations of their properties based on particle views.
LO 2.3: The student is able to use aspects of particulate models (i.e., particle spacing, motion, and forces of attraction) to reason about observed differences between solid and liquid phases and among solid and liquid materials.
LO 2.5: The student is able to refine multiple representations of a sample of matter in the gas phase to accurately represent the effect of changes in macroscopic properties on the sample.
LO 2.9: The student is able to create or interpret representations that link the concept of molarity with particle views of solutions.
LO 2.15: The student is able to explain observations regarding the solubility of ionic solids and molecules in water and other solvents on the basis of particle views that include intermolecular interactions and entropic effects.
LO 2.25: The student is able to compare the properties of metal alloys with their constituent elements to determine if an alloy has formed, identify the type of alloy formed, and explain the differences in properties using particulate level reasoning.
LO 3.1: Students can translate among macroscopic observations of change, chemical equations, and particle views.
LO 4.8: The student can translate among reaction energy profile representations, particulate representations, and symbolic representations (chemical equations) of a chemical reaction occurring in the presence and absence of a catalyst.
LO 5.2 The student is able to relate temperature to the motions of particles, either via particulate representations, such as drawings of particles with arrows indicating velocities, and/or via representations of average kinetic energy and distribution of kinetic energies of the particles, such as plots of the Maxwell–Boltzmann distribution.
LO 6.11: The student can generate or use a particulate representation of an acid (strong or weak or polyprotic) and a strong base to explain the species that will have large versus small concentrations at equilibrium.
LO 6.24: The student can analyze the enthalpy and entropic changes associated with the dissolution of a salt, using particulate level interactions and representations.

from our own experiences as students. As discussed above, there are few examples of assessment items available in previously released AP Chemistry Exam materials. Some textbook authors have been noted[4] for making extensive use of particulate representations, e.g., McMurry and Fay[20] and Williams and Olmstead,[21] but not all classrooms will have access to such texts. Simulations and animations that provide dynamic particulate representations have become widely available through the worldwide web but educators may have limited experience using these effectively in the classroom. Furthermore, many educators may be unaware of the challenges of helping students learn how to interpret particulate representations, both dynamic and static. Thus, many teachers may find themselves in need of information and resources on teaching particulate representations.

The goal of this review is to provide a concise introduction for teaching chemistry with particulate representations. Where research exists in the effectiveness of each technique that research is noted. Although the impetus here is the revised AP Chemistry curriculum, these ideas are equally applicable to any introductory chemistry course at the high school or college level.

■ THEORY AND GENERAL CONSIDERATIONS

The Three Domains of Chemical Knowledge

Chemical knowledge can be thought of as existing in three distinct levels or domains:[22,23] macroscopic and tangible, symbolic and mathematical, and submicroscopic or particulate. For example, consider the compound copper(II) carbonate (Figure 1). Symbolically, we represent this compound using the

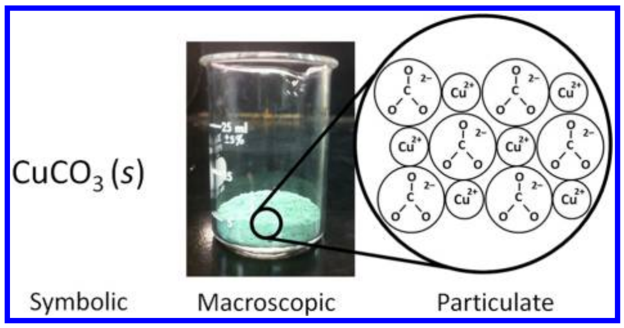

Figure 1. An example of the three domains of chemical knowledge: The compound copper(II) carbonate can be symbolically represented with its chemical formula. In the lab, it is encountered as a powder. Its particulate domain is represented with a drawing of a two-dimensional lattice showing an equal number of positive and negative ions.

formula $CuCO_3(s)$. Macroscopically, this compound is often encountered in the lab as a light blue powder used in decomposition experiments. In the particulate domain, copper(II) carbonate is composed of repeating units of Cu^{2+} and CO_3^{2-} ions. The particulate domain cannot be directly observed, but it is useful to think about particles by creating representations of them. The particulate representation in Figure 1 emphasizes that $CuCO_3$ is ionic and is composed of a lattice of positive and negative ions, not neutral molecules. The use of lines to connect the C and O atoms in carbonate is meant to emphasize that the carbonate polyatomic ion is composed of atoms that are covalently bound to one another even though the overall bonding of the compound is ionic.

In general, every concept we study in chemistry can be formulated as some combination of the three domains shown in Figure 1.[22,23] Solving problems in chemistry often requires moving from one domain to another, which is quite challenging for many students.[3,24] Traditional lecture courses in chemistry have tended to emphasize the symbolic/mathematical domain,

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while laboratory courses have tended to emphasize macroscopic quatities such as visual appearance, color, temperature, pH, and so forth.[25] This leaves insufficient emphasis on the particulate domain and the literature shows that many students fail to learn it. In the absence of a conceptual understanding of chemistry, students rely instead on algorithmic processes to solve problems without understanding the underlying concepts.[3] The challenge, then, is to find ways to help students develop a conceptual understanding of the particulate domain and the ability to use and generate their own representations of that domain to solve problems.

Particulate Representations as Models

Novice students often interpret models of all kinds as exact replicas of reality.[26] However, it is impossible for any drawing, animation or other model to exactly replicate atomic-level phenomena, nor is it pedagogically sound to make a model overly detailed.[27,28] In making a model it is therefore necessary to make certain choices about what is shown and what is emphasized. Consider the particulate representation in Figure 1. The diagram was designed to emphasize that the ions are stacked in a repeating array (a lattice) that contains ions that are close together as would be the case in a solid; the 1:1 ratio of cations to anion; the presence of charges on ions; the presence of both ionic and covalent interactions; and that the multiatom, negatively charged carbonate ion is larger than the positive Cu^{2+} ion. The diagram does not convey all details of $CuCO_3$ at the particulate domain including that (1) lattices are three-dimensional, (2) the compound is generally found as a hydrate with water molecules integrated into the crystal structure, (3) the crystal structure is not cubic as implied by the diagram but rhombohedral, and (4) that carbonate is planar and thus does not look like a sphere as implied by the figure. Thus, the diagram in Figure 1 is insufficiently detailed for an advanced course in solid state chemistry but is appropriate for teaching introductory chemistry courses in which we seek to help students understand bonding in ionic, molecular and metallic solids. Furthermore, the particulate representation in Figure 1 is at the level of the drawings we would expect students to produce in a quiz or exam setting. In other words, the level of detail has to be chosen to suit the learning objective and the needs of the learner.

As they do with all models, students may struggle with particulate representations if they interpret them as exact copies of reality, thinking of them more like photographs than simplified depictions.[24,26,29] Students also have difficult moving from one representation of a problem to another,[24] even from an animation to a drawing.[30] It is therefore important to help students understand the limitations of various particulate representations.

Misconceptions: Problems and Opportunities

Asking students to draw particulate representations can also reveal students' misconceptions. A misconception (or alternate conception) is a concept of the learner that differs from the accepted, or expert, scientific concept.[8,31] For example, students often believe incorrectly that matter is continuous, that atoms expand when they are heated, or even that atoms are alive.[8,32] Misconceptions may be based on conceptual frameworks that students' have prior to instruction.[8] Those frameworks are not simply replaced when students receive instruction in scientifically accepted concepts.[33] It is worth noting that some researchers have taken a more nuanced approach to misconceptions, thinking of students' concepts less in terms of right or wrong and more in terms of evidence of progress toward a more scientifically accepted concept.[34−36] In the context of teaching with particulate representations, misconceptions may be best thought of as evidence that students enter the classroom with their own conceptions of matter. Their prior conceptions make it difficult for them to construct mental models that fully encompass the atomic-molecular and kinetic molecular theories. Helping students develop mental models that reflect accepted scientific theories then becomes the primary goal of instruction.[36] It is also important to think carefully about how one introduces particulate representations to avoid creating new misconceptions.

■ INTRODUCING PARTICULATE REPRESENTATIONS TO STUDENTS

Given that students' success on particulate questions increases with exposure and instruction using particulate representations,[27,37,38] it is important to introduce particulate representations early and use them throughout the course. One of the first subjects many teachers cover in introductory chemistry classes is classification of substances as pure substances, compounds, and mixtures. This can be an excellent topic for introducing particulate representations rather than treating the subject as merely vocabulary. Figure 2 is an example of a particulate

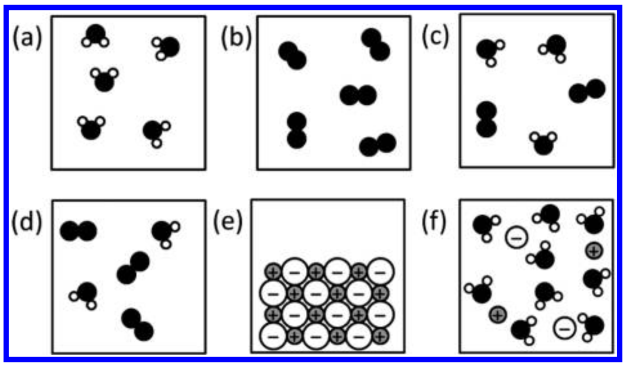

Figure 2. Particulate representations of several substances: (a) pure water vapor, (b) pure O_2 gas, (c) a mixture of O_2 gas and H_2O gas, (d) a different mixture of O_2 gas and H_2O gas, (e) pure solid NaCl, (f) a homogeneous mixture (solution) of NaCl and liquid water.

representation that can be used to introduce these concepts. The diagram shows examples of pure substances, compounds, and mixtures. Diagrams like this one have been used in studies that demonstrated increased conceptual understanding with the use of particulate representations.[37] These types of diagrams also make excellent models for POGIL activities (see below) such as the one in ref 39 (p 39−46). Such a diagram also provides a basis for discussing the difference between compounds that form discrete molecules (such as water) and ionic compounds which do not (like sodium chloride). Students can also be asked to provide their own key to such diagrams to practice switching between particulate and symbolic representations, although these keys should be checked carefully for understanding.

Diagrams like Figure 2 also introduce students to some of the conventions of drawings as particulate representations which are, by necessity, both two-dimensional and static. Each atom is represented as a separate circle. This makes it possible to show the correct shape of water, setting the stage for VSEPR later, and helps avoid the misconception that water molecules are spherical.[32]

An important issue to address with students is the white space between particles in particulate representations. In a representation of an aqueous solution it may be too difficult and confusing to show all of the water molecules present, so the white space represents the molecules of water. In a representation of a gas such as Figure 2a–d, the white space is in fact empty space or vacuum, but many novice students will label this space as air.[32] Since many students have the misconception that matter is continuous,[8] it is likely that students are trying to accommodate their particulate-domain knowledge with their misconception of continuous matter. To overcome such misconceptions, it is important to consistently ask students to label the white space in particulate representations whether it be empty space (in a gas), water (in an aqueous solution), or even free electrons when discussing the "electron sea" model of metals.

Another issue with particulate drawings arises when trying to show motion of particles. Figure 3 shows a particulate

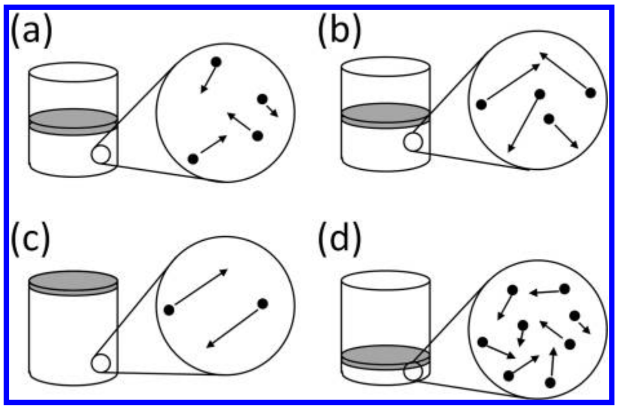

Figure 3. A macroscopic and particulate representation of the gas laws. (a) A sample of helium gas in a closed piston–cylinder at 298 K; (b) the gas after being subjected to increased temperature at constant volume; (c) the gas after the temperature is increased at constant pressure; (d) the gas after the external pressure is increased at constant temperature. Remind students to label the white space in between particles, here empty space.

representation of a sample of helium gas under various conditions. Arrows are used to represent the direction of movement and the length of the arrows indicate the relative speed of each particle (see Box 1, LO 5.2). One way to introduce this is to show students computer animations that show the motion of the particles (see below) then introduce drawings like Figure 3. Since students have trouble constructing representations from other representations,[30] they will need guidance and practice to produce drawings of their own after watching an animation. It should also be pointed out to students that the arrows do not represent forces acting on the particles unlike free body diagrams from physics. This compounds a physics misconception that any object in motion is doing so because it is experiencing a force.[35]

Students will need scaffolding as they begin to create particulate representations like those in Figure 3. For gases, there are two main considerations: the concentration, which affects the number of particles in the magnification window, and the temperature, which affects the speed of particles as indicated by the length of the arrows. For example, the change in Figure 3a to 3b represents an increase in temperature at constant volume. Ask students if the macroscopic volume has changed and how this affects the concentration. Since the volume is unchanged, the concentration remains unchanged. Then ask them how the temperature has changed (it is increased), and ask them how they will indicate this (longer arrows). Students can then be asked what macroscopic quantity will change as a result of the increase in temperature (the pressure), then asked to write an equation they would use to calculate this change quantitatively ($P_1/T_1 = P_2/T_2$).

There are two common forms of particulate drawings that students will encounter, those that use a magnification window (as in Figures 1 and 3) and those that do not (as in Figures 2 and 4). The magnification window is meant to

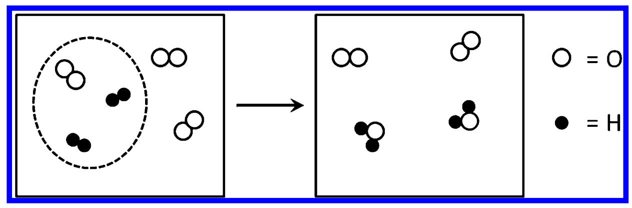

Figure 4. An example of a particulate representation of a limiting reactant problem for the reaction $2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$. Oxygen atoms are represented by white circles and hydrogen atoms by smaller black circles. In this case, two hydrogen molecules react with one oxygen molecule to form two water molecules and two oxygen molecules as in excess. The molecules that react to form products have been outlined for emphasis. The white space is empty space. Here a representative sample of particles are shown rather than using a magnification window. This allows students to focus on conservation of particles rather than concentration.

emphasize that (1) atoms and molecules are very small and (2) only a small region inside the sample is being viewed. This is more appropriate when thinking about the concentration of a sample, either in the gas (Figure 3) or solution phase (Figure 5). However, the magnification window can lead to confusion because students might believe that particles are not conserved. Furthermore, the magnification window may be taken to indicate that we can see gaseous atoms under a microscope, which we cannot.[40] For these reasons, particulate representations may instead show some representative sample of the particles in a sample. This is particularly true of stoichiometry problems in which we wish to emphasize conservation of particles. Figure 4 shows a limiting reactant problem in which students have to use the balanced reaction equation to determine the number of water molecules produced and, in this case, the number of oxygen molecules in excess. The reactant molecules that undergo the chemical change to water are circled for emphasis. In this case, the total number of particles changes from five to four, so representing these in a magnification window can be difficult.

Representing the particles without the magnification window may seem easier, but it can raise problems of mixed scales. Students might infer that atoms and molecules are larger than they actually are. To avoid creating this misconception, it is best to avoid showing molecules moving around an entire container like a beaker or a piston. Students are likely to encounter both diagrams with and without magnification windows in their textbooks,[20,21] so it is important to discuss with students what these models actually represent. An excellent way to help students grasp the scale for the particles these drawings represent is to show them an animation successively showing the universe at 10 times greater magnification.[41,42]

SPECIFIC TECHNIQUES FOR TEACHING PARTICULATE REPRESENTATIONS

Below are specific suggestions for integrating particulate representations throughout an AP or other introductory chemistry course. Student performance on particulate questions increases with exposure and practice.[27,37,38] As such, a variety of techniques and means of integrating particulate representations are given below, and it is important to use as many as possible to help students develop fluency with particulate representations.

Teaching with Inquiry

Inquiry education is a student-centered and active learning pedagogy in which students move from evidence to theory instead of the other way around as is typical in traditional teaching.[43,44] In this context, the teacher act as a facilitator of learning rather than the source of all knowledge. Inquiry centers around the learning cycle of exploration, concept invention and application. First, students explore data in the form of lab data or data provided by the instructor in the form of a table, graph, diagram, animation, etc. Then, students are led to create (or "invent") the new concept. Finally, students apply the new concept in different contexts to ensure understanding and to raise new questions for future learning cycles.

Inquiry-based activities offer an excellent opportunity for students to learn to draw and communicate through particulate drawings because students can be forced to investigate particulate representations, draw conclusions from them and construct their own meaning from them.[36] Inquiry activities come in many forms, but one particularly well suited for AP Chemistry is the POGIL method (Process Oriented Guided Inquiry Learning) in which students work in small (3–4 students) groups on guided inquiry activities.[45,46] POGIL activities have been found effective for improving student learning outcomes.[45] POGIL authors make extensive use of particulate models in their activities. Two appropriate collections for AP Chemistry commercially available are *POGIL Activities for High School Chemistry*[39] and *Chemistry: A Guided Inquiry*.[47] Another excellent source of inquiry-based materials is the Target Inquiry project.[48] Many of these activities use particulate representations. Two of these activities were used in a study that demonstrated the effectiveness of merging inquiry instruction with particulate representations.[36]

Use Animations and Simulations

Animations as teaching tools have been studied in more detail than most particulate representations, and have been shown to improve students success in situations in which the movement of particles is important,[15,27,49] with the greatest benefit seen for female students.[38] Working with dynamic models can help students begin to visualize the movement of gas particles and be more likely to generate drawings like those in Figure 3. When teaching with animations, it is important to consider students' cognitive load because a large amount of information may be presented at once, not all of which is relevant to the intended learning objective.[27,28] One of the most useful scaffolding techniques is to narrate an animation while your students watch it to direct their attention to the most important aspects.[28]

The PhET[50] and MoLE[51] Web sites offer many well designed animations that show representations of phenomena in all three domains (macroscopic, symbolic, and particulate) simultaneously. These include animations on gas laws, molarity, shapes of molecules and electrochemistry. Of note is the PhET simulation of acid–base chemistry that allows students to change the concentration and acid strength (effectively the K_a of the acid) while watching the pH and the particulate representation change (Box 1, LO 6.11). The PhET simulation "Gas Properties" would be useful to pair with a discussion of pencil and paper drawings like those shown in Figure 3.

The Molecular Workbench[52] is a downloadable program which also provides good particulate simulations. The 2D water simulation is an excellent visualization of liquid water transforming to solid water as the system is cooled. As the thermal energy decreases, the force of the hydrogen bonds can be seen pulling the molecules together. The molecules still vibrate but are no longer moving past one another as in the liquid. This sort of visualization is essential for students to begin making the kind of mental models necessary to answer questions related to LO 2.3 (Box 1).

Asking Paired Questions

Given the emphasis on particulate representations and the de-emphasis of calculations, it makes sense to ask students to accompany most calculations with particle-level drawings that match or justify their calculation. Paired conceptual–calculation questions have been used in research assessment[5−7,14] and end of course assessment.[53] Their use in formative assessment (see below) in the classroom has not been studied, but they should be an effective means of helping students make connections between calculations and concepts.

As an example, consider a common question about dilution. Students might be asked how to prepare 100 mL of 0.10 M solutions of KCl, $MgCl_2$, and HF starting from 0.20 M stock solutions of each. Following this algorithmic calculation (often done using the equation $M_1V_1 = M_2V_2$), students could be given a representation of 0.20 M KCl as shown in Figure 5a, then asked to draw particulate representations of the diluted solutions for each of the 0.10 M solutions (Box 1, LO 2.9).

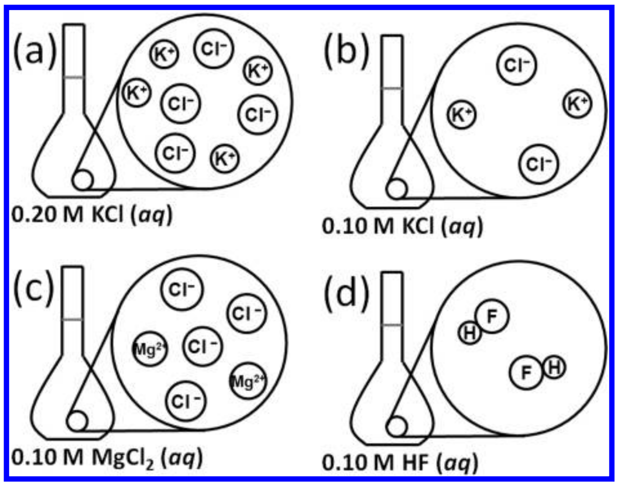

Figure 5. Particulate question to accompany molarity calculations. After asking students to perform a routine dilution calculation, students can be asked to then draw particulate representations of the diluted solutions given the original 0.20 M KCl solution in (a). Students could then be expected to draw representations of solutions of (b) 0.10 M KCl, (c) 0.10 M $MgCl_2$, and (d) 0.10 M HF. Students should be reminded to identify the white space in particulate representations. Here, the white space is water.

Creating such particulate representations is nontrivial for students in part because they have to call on knowledge from earlier in the course and which is not immediately apparent

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from the calculation. Students frequently struggle with correctly determining the ratio of particles (both within one sample and between samples) and whether or not to represent species as dissociated ions or as molecules. In the example in Figure 5, students would have recognize that because the 0.20 M solution has four formula units in the particulate representation, the diluted solutions should have two formula units of KCl and $MgCl_2$ and two (nondissociated) molecules of the weak acid HF. The weak acid HF provides a good opportunity to point out that even though HF dissociates to a tiny extent in aqueous solution it would be unlikely to find a dissociated molecule of HF in a sample of just two HF molecules. When scaffolding these problems for students, then, it is necessary to ask students to think about three main issues: (1) what the concentration (in mol/L) tells us about the number of particles to show in the magnification window, (2) for ionic compounds, what is the ratio of cations to ions based on the chemical formula, and (3) should the particles be associated (weak acids) or dissociated (soluble salts and strong acids).

Use Particulate Representations To Reinforce Laboratories

Another strategy is to ask student to summarize the results of demonstrations and laboratories in terms of all three domains. In the lab setting, after performing the classic hydrate decomposition lab with $CuSO_4 \cdot 5H_2O$, students can be asked at the end to explain the results in terms of (1) their math and the formula that expresses the mole to mole ratio, (2) the visual evidence they saw that justifies their formula (i.e., change or color, evolution of water vapor), and (3) a drawing of the compound at the particulate level before and after heating.

The MORE model (Model-Observe-Reflect-Explain)[54] asks students to refine their particulate representations by comparing what they think is happening at the particulate level to their laboratory observations. It has been found effective at enhancing students' understanding of the particulate domain.[55]

Physical Models

Even with the possibilities brought on by computer simulations, it remains important for students to have tactile experiences with physical models. These may include using traditional ball and stick models to explain the hardness and extremely high melting point of diamond (Box 1, LO 2.29 and 2.30). Models of water molecules with imbedded magnets (such as those from 3D Molecular Designs) can help students develop an accurate conception of hydrogen bonding and phase transitions. The same company offers an excellent (though somewhat expensive) magnetic model for understanding ionic lattices. Another excellent model for visualizing solids uses small rare-earth magnetic spheres to represent atoms in solids.[56]

Physical models also provide an excellent opportunity to discuss the scope and limitations of models.[26] For example, ball and stick models provide an excellent opportunity to discuss the difference between the representation (the stick) and what is it represents (an attractive force).

Particulate Role Play

Having students represent particles themselves is another way to model particles. The Boltzmann game[57] is an effective role play for simulating energy distributions leading to a Boltzmann distribution (Box 1, LO 5.2). Each student begins the role play with five pieces of play money ("Joule bucks") and then plays multiple rounds of rock-paper-scissors with other students with the winner receiving a Joule buck from the loser of each round. After students play enough rounds to have the money distributed in a statistically random manner, the students reassemble as a class and make a histogram of Joule buck distribution which, inevitably, closely mimics the Maxwell–Boltzmann distribution. This is a great way to introduce a concept that is very abstract for students. However, it is important for student to grasp the various aspects of the analogy, especially that the students represent particles, the Joule bucks represent the amount of kinetics energy per particle and the rock-paper-scissors game serves to randomly (but unevenly) distribute energy throughout the system.

Role play can also been used to help visualize particles in demonstrations.[58] In my classroom, student perform a role play to interpret the reaction between copper metal and silver nitrate solution (Box 1, LO 3.1). We first observe the reaction in the beaker, then student hold cards showing their initial identification as Cu(s), Ag^+(aq), or NO_3^-(aq). I then guide them through the reaction as one Cu atom exchanges one electron with each of two Ag^+ ions. As the students "react" they flip their cards to show they are now Ag(s) and Cu^{2+}(aq). The students representing nitrate get an unexciting lesson about the role of spectator ions in the solution—they do not undergo reaction but still provide the negative charge to maintain charge neutrality in the solution. We refer back to this role play when we discuss stoichiometric ratios and limiting reactants.

Formative Assessment To Test for Learning

Formative assessment is the practice of probing students' understanding in order to help students and teachers gauge how well students have learned a subject and determining if additional instruction is needed.[2,59] Formative assessment, whether in the form of in-class practice problems, homework problems or quizzes, can provide feedback for both students and teachers for the effectiveness of instruction as well as to check for misconceptions. The results of such formative assessment—and student questions generated from the assessment—can then inform instructional decisions about whether to continue to a new topic or to provide remediation.

Any of the figures in this article could be used to create a formative assessment question. For example, students could be given the particulate representation in Figure 2a then asked to draw representations of the gas particles after each transformation. Student work should be checked for correct use of longer arrows at higher temperatures and being consistent about the number of particles shown, e.g., if the volume doubles the density of particles is half the original. Diagrams testing conceptual understanding of stoichiometry, like Figure 3, can reveal many misconceptions, including drawings of molecules that do not correspond to the reaction equation symbols or drawings that contain no atoms at all.[11,13] Another way to use this as formative assessment would be to provide students with Figure 3 (without outlining the molecules that react) and ask students to provide a reaction equation.

Any of the techniques listed above can serve as a means formative assessment. Facilitation of guided-inquiry activities involves constant formative assessment as students answer questions and ask for guidance. When using animations, students can be asked to make predictions of particulate behavior before changes (e.g., raising the temperature) are made to the animation. Students can be asked to design their own role play activities for new situations, e.g., a different reaction. Asking students to label white spaces and create their own keys to particulate representations also helps monitor student understanding. When used in this way, formative assessment can become a routine and embedded aspect of classroom instruction, and provide the opportunity to monitor and correct students' understanding of very abstract concepts.

■ CONCLUSIONS

Nearly 30 years of research has increased our appreciation for the need to explicitly teach students to think about chemistry at the level of atoms, molecules, and ions. Teaching with an emphasis on developing deep conceptual understanding with particulate representations instead of teaching algorithms can be as rewarding as it is challenging. In my own experience at both the high school and college level, students respond well to discussions of particulate representations. Many students are excited to develop their conceptual understanding because it helps them see chemistry as a framework for understanding nature rather than a series of disconnected equations and calculations. That said, teaching particulate representations requires persistence because many students struggle to develop the necessary mental models of particulate behavior. Embedding particulate representations in all aspects of the course and using a variety of techniques is necessary to cultivate the deep conceptual understanding students need to be successful on the AP Chemistry Exam and in their future chemistry courses.

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Notes

The authors declare no competing financial interest.

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