An Interdisciplinary Study of Student Ability to Connect Particulate and Macroscopic Representations of a Gas

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Abstract. This interdisciplinary project assessed the extent to which students in general education courses across two departments understood the assumptions of small-particle models and the ways in which these models relate to measurable properties. As part of this project, we embedded conceptually-oriented questions on written assessments in general education courses in physics and chemistry. Questions were drawn from the published literature in chemical and physics education and were developed by the research team. The results of this project provide a baseline measurement of the extent to which a diverse population of students in introductory physical science courses was able to develop and use particulate models to reason about macroscopic observables.

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INTRODUCTION

The small-particle model of matter is among the most fundamental models in physical science, and is at the core of modern science. Students are exposed to this idea early in their educational careers, but there is evidence that many students have difficulty in understanding aspects of the model. Most of the studies of student understanding of these ideas have taken place with precollege students [1,2].

Most universities require that students complete courses in introductory science, as part of general education (GE) requirements. These courses typically have a broader focus and often address fundamental ideas like the small-particle model for matter. At California State University Fullerton (CSUF), one of the GE goals for physical science states that students should understand the following: "All matter has observable properties that depend on the conditions and scale at which we look. Investigations of matter at the atomic and subatomic levels explain the properties, reactions and interactions of matter." (http: www.fullerton.edu/senate/PDF/400 /UPS411-201.pdf - 2004-07-21)

The authors participated in a campus-wide effort to assess the GE program, and sought to document the level of student understanding of particulate models of matter and their connections to macroscopic observable quantities, with a focus on courses offered by two departments: Chemistry and Biochemistry, and Physics. The current report describes a portion of this effort in the context of gas behavior. Other aspects of this project include studies of student understanding of physical and chemical changes, solutions, and common representations of particulate models and will be described in further publications.

DETAILS OF THE RESEARCH

This work proceeds from the assumption that students construct understanding of scientific phenomena, in some cases developing ideas that are in contrast with accepted scientific viewpoints. We have sought to document student understanding of the target ideas using standard methods of science education research. We developed conceptual questions for use in course assessments as well as individual student interviews. We were interested in the extent to which students could connect the small-particle model and the macroscopic world, in an extension of previous research which focused on adapting given small-particle gas models [3,4]. Thus we used questions in which students were given information in one way and asked to make predictions in terms of the other. Although we have posed questions in a variety of courses after traditional instruction, our goal was not to assess instruction or any specific curriculum. Rather, we hoped to determine a baseline level of student understanding and the extent to which these ideas are difficult for students in the GE program.

Research Questions

To what extent can students interpret a particulate illustration and use the illustration to predict changes in macroscopic observables?

To what extent can students draw particulate illustrations that correspond to stated changes in macroscopic observables?

To what extent do these results vary for different student populations, including different courses levels as well as different departments?

Context for Research

This study was performed in the context of several courses at California State University Fullerton (CSUF), a public comprehensive university serving a diverse student population. CSUF is the largest university in California, serving over 37,000 students.

Two of the courses, described as 'Survey Physics' and 'Survey Chemistry,' enroll primarily non-science majors, and are typically taken by students in order to satisfy a GE requirement. Both courses are taught in a traditional large lecture format, meeting three hours per week with an optional three-hour lab component. A third course, described as 'Introductory Chemistry,' is intended to prepare students for General Chemistry. This course emphasizes problem-solving and meets in a computer studio classroom setting, with opportunities for work in small groups. Most of the students in Introductory Chemistry intend to major in a natural science or engineering, and many aspire to health-related careers. The final course, described as 'General Chemistry,' is a calculus-based course for science and engineering majors. This course is taught in a reformed format, incorporating recitation and lecture to allow large and small group work two hours three days per week, and also has a three-hour lab. General Chemistry is often taught by two of the authors of this study.

Students in the study completed all instruction on gas laws in their course before delivery of the research items. While gas laws are taught at least briefly in each of the target courses, most of the courses devote relatively little time to particulate models of a gas, based on the presumption that such a model has been taught and understood in secondary school.

Methods

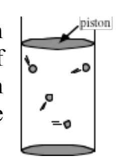
All data in this paper were collected by analysis of student responses to questions posed on course examinations and quizzes (both graded and ungraded, depending on the wishes of the course instructor). The questions were constructed based on examination of the research literature as well as previous work by the authors. Students were asked to provide an answer, often including a drawing, as well as a written explanation. Student research assistants performed data entry and analysis with consultation by the study authors. Student answers and explanations were classified and assigned codes. The study authors performed rater reliability checks in order to verify the validity of the codes. After several iterations of the coding scheme, the student coding agreed with expert coding over 80% of the time.

Research Items

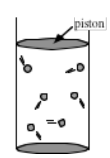
As noted, our goal for research items was to provide students with information at one level (macroscopic or particulate) and ask that they make predictions at the other level. The two problems described below use a representation that is common to textbooks, in which a cylinder of gas is closed by a piston, with the gas shown as discrete particles. We recognize that this representation is problematic due to the scale of the particles relative to the container, but used it due to its familiarity. To distinguish the two problems, we describe them as GAS_PtM (particulate to macroscopic) and GAS_MtP (macroscopic to particulate).

In GAS_PtM (see Figure 1), students are shown an initial illustration with four gas particles. The problem then shows two revised illustrations, one with six particles and the same piston height, one with four particles and a lower piston height, and asks students to state whether the pressure and volume of the gas would increase, decrease, or remain the same, and explain their reasoning.

Consider the model for a container filled with an ideal gas (diagram at right). For each of the parts below, examine the new diagram and predict how, if at all, each of the macroscopic quantities listed will change.



Part A. (increase the number of particles)
Volume: *increase/decrease/ stay the same/can't tell*
Pressure: *increase/decrease/ stay the same/can't tell*



Part B. (decrease piston height)
Volume: *increase/decrease/ stay the same/can't tell*
Pressure: *increase/decrease/ stay the same/can't tell*

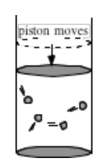
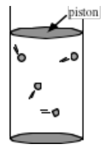


FIGURE 1. Research item GAS_PtM

In GAS_MtP (see Figure 2), students are shown the same initial illustration. They are then asked to sketch the number of particles and the height of the piston in a new diagram that would be consistent with changes in the macroscopic variables (volume increases while pressure and temperature remain constant), and explain their reasoning.

Consider the model for a container filled with an ideal gas (diagram at right). The container is closed by a piston that can move up or down. The gas particles are moving and interact with one another only when they collide (assume that all collisions between gas particles are elastic.



Changes are made to the initial state of the gas shown in the diagram. Each change is described in terms of the macroscopic observable quantities (e.g., pressure, temperature. Sketch a diagram that is consistent with the macroscopic change described, showing the location of the piston and the particles that make up the gas. If the diagram does not change, state so explicitly. If the change is not possible as described, state so explicitly.

The volume of the gas is increased while pressure and temperature remain constant.

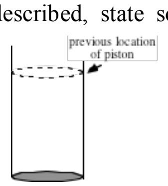


FIGURE 2. Research item GAS_MtP

RESULTS AND DISCUSSION

The frequency of correct responses to item GAS_PtM is provided in Table 1. For Part A, the correct response is volume remains the *same* and pressure will *increase*. For Part B, the correct response is volume will *decrease* and pressure will *increase*.

TABLE 1. Percent frequency of correct responses for item GAS_PtM

		Part A	
Course	**N**	**Volume**	**Pressure**
Survey Physics*	62	52%	55%
Survey Chemistry**	102	56%	74%
General Chemistry**	235	67%	74%
		Part B	
Survey Physics*	62	61%	77%
General Chemistry**	235	83%	93%

*Item delivered as part of an ungraded assignment (quiz)
**Item delivered as part of a graded assignment (exam for Survey Chemistry and quiz for General Chemistry)

A majority of students answered correctly in each class. The incorrect answers given by students reveal significant difficulties in interpreting and applying the particulate model for a gas as well as the macroscopic operational definitions of volume and pressure.

A number of students answered the volume questions incorrectly, despite the fact that the volume should be clear from the illustration. For example, in Part A, the piston height is unchanged. However, a significant number of students predicted that the volume would *increase* (32% for Survey Physics, 32% for Survey Chemistry and 29% for General Chemistry). Similarly, in Part B the piston is moved downward, but the second most common response was volume would remain the *same* (24% for Survey Physics and 15% for General Chemistry). In both cases, student responses are consistent with use of the particulate components of the illustration to predict the volume of gas. In effect, students seem to relate the number of particles to the volume. For the subset of students that related number of particles to volume (N=29 for Survey Physics and N=73 for General Chemistry), the percent frequency of students in this subset that selected both *increase* in Part A and *same* in Part B was 21% for Survey Physics and 43% for General Chemistry, suggesting that General Chemistry students tend to use particulate models more when reasoning about changes in macroscopic quantities.

The pressure questions elicited more correct answers than volume. In terms of predicting change in pressure, the second most common response for Part A was *same* (34% for Survey Physics, 21% for Survey Chemistry and 19% for General Chemistry). For Part B, the second most common response for pressure was *decrease* (16% for Survey Physics and 5% for General Chemistry). These answers are consistent with students applying Boyle's law to predict pressure based on volume, but applying the (incorrect) direct proportion between volume and pressure for Part B. However, preliminary examination of explanation statements also found that some students related pressure to the position of the piston in the cylinder, consistent with the previous report by Kautz et al. [5,6]. We have sought to develop a general coding scheme for student reasoning statements that can be applied to any question of this type. We plan to report on this reasoning coding scheme at a later date.

The frequency of responses for drawing the particulate illustration in item GAS_MtP is provided in Tables 2 and 3. Two components of the illustration were coded: piston height (which is directly related to volume) and number of particles. The coder noted a comparison of each component to its value in the original illustration provided in the item. Because the problem states that volume increases, the correct response is that the piston height must increase. With the constraints that pressure and temperature remain constant, application of the ideal gas law shows that the number of particles must *increase*. Table 2 shows the frequency of responses that illustrated an increase in piston height (for any number of particles) and an increase in number of particles (for any piston height).

TABLE 2. Percent frequency of responses for illustrating an increase in piston height (H) and an increase in number of particles (N) for item GAS_MtP

Course	N	Increase H	Increase N
Survey Physics*	62	32%	23%
Intro. Chemistry*	73	53%	16%
General Chemistry**	495	6 %	43%

*Item delivered as part of an ungraded assignment (quiz for Survey Physics and exercise for Introductory Chemistry)
**Item delivered as part of a graded assignment (quizzes and exams)

The MtP problem was more challenging for students. Many students gave a written answer but did not complete the illustration, either omitting the piston height (53% for Survey Physics, 37% for Intro. Chemistry, and 23% for General Chemistry) or the number of particles (57% for Survey Physics, 23% for Intro. Chemistry, and 29% for General Chemistry). For the piston height, the other common incorrect answer was to show the piston at the same height despite the volume change (11% for Survey Physics, 4% for Intro. Chemistry, and 11% for General Chemistry). Many students drew the same number of particles (18% for Survey Physics, 56% for Intro. Chemistry, and 26% for General Chemistry). Few students illustrated a decrease in piston height or number of particles.

Table 3 shows the frequency of responses for the most common combination of piston height and number of particle components in the illustrations.

TABLE 3. Percent frequency of illustration responses for piston height (H) and number of particles (N) for item GAS_MtP

Illustration Components**	Survey Physics	Introductory Chemistry	General Chemistry
Increase H*			
Increase N*	5%	11%	33%
Same N	15%	34%	19%
Omitted N	13%	7%	12%
Same H			
Increase N	5%	1%	5%
Same N	2%	3%	3%
Omitted N	5%	0%	1%
Omitted H			
Increase N	11%	3%	4%
Same N	2%	15%	2%
Omitted N	39%	16%	16%

*Correct response is an increase in piston height and number of particles.
**The illustration components of decrease H and decrease N had very low responses and are omitted from the table.

From Table 2, more students correctly illustrate the macroscopic component, piston height, based on the change in the macroscopic quantity, volume. However, fewer students were able to correctly illustrate the particulate component, number of particles, based on the macroscopic quantities provided. In contrast to the PtM problem, in which students predicted a macroscopic quantity based on a particulate illustration, far fewer students were able to provide a particulate illustration based on a macroscopic quantity in the MtP problem. For example, an average of 57% of Survey Physics students were able to predict volume based on the height of the piston in Part A and B of the PtM problem; this decreased to 32% who were able to illustrate piston height based on volume.

SUMMARY

While this work is still preliminary, there are strong indications of a significant disconnect between particulate models of a gas and macroscopic observable phenomena. In situations where particulate components change between illustrations, students were less successful in predicting changes in macroscopic quantities. Survey Physics students are less likely than chemistry students to consider particulate components to predict changes in macroscopic quantities. In general, students are more successful in linking the particulate to macroscopic realms than the macroscopic to particulate realms.

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