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In the Classroom

Testing for Conceptual Understanding in General Chemistry[1]

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Assessment of student learning is an important and timely issue across all areas of science education.

Conceptual understanding involves being able to represent and translate chemical problems using three forms of representation—macroscopic, particulate, and symbolic. In addition to research on chemical problem solving, a great deal of work on student misconceptions involving chemical phenomena has been conducted. Both the representational formats, and the work on student misconceptions, served as framework for a team of chemical educators to develop a general chemistry standardized exam focused on conceptual understanding that is now available from the ACS Examinations Institute. Several of

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[1] Presented at the 213th National Meeting of the American Chemical Society, San Francisco, CA, April, 1997, (CHED #811).

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the item formats differ from the conventional single answer multiple choice question currently used on such tests. This article will report the background of the test, the structure of the test, and on-going work of the group.

A recent national survey on assessing student learning indicated that the two most valued learning outcomes held by faculty for college chemistry students are the understanding of chemical concepts and the ability to use those concepts to solve various chemical problems [1]. Concepts (or ideas) are mental constructs that people make to understand various aspects of the world. For example, in chemistry students need to understand concepts such as the mole, rates of reactions, atoms and molecules, heat and temperature, and free energy. Gabel and Bunce [2] in their comprehensive review on problem-solving research in chemistry suggest that one of the main reasons students have difficulties solving some chemical problems is that they lack understanding of the concepts needed to solve the problems.

Because of its prevalence in the literature, it is important to consider distinctions between the algorithmic and conceptual questions we ask students [e.g., 3, 4]. Consider the two pairs of items in Figure 1. *Algorithmic questions* can be answered by applying a set procedure to generate a response. The algorithm may be of a quantitative nature, such as solving the stoichiometry question in item 1 (algorithmic). Algorithmic items, however, need not be quantitative. In item 2 (algorithmic) the students utilize an algorithm that considers the number of electron regions and matches that with memorized bond angles. *Conceptual questions* try to tap into the “why” aspect of a response that indicates understanding of chemical ideas associated with the question. A conceptual question may be of a quantitative nature such as item 1 (conceptual). The respondent may use an algorithm to solve the item, or they can apply the idea of conservation of mass to realize that the MgO must have a greater mass than the original Mg. Conceptual questions may be of a qualitative nature that require students to relate different ideas (e.g., how electronic density impacts molecular structure, item 2).

Assessment of student learning is an important and timely issue across all areas of science education [5]. Because conceptual understanding in chemistry is a valued learning outcome in the chemistry education community, it is an outcome that we need to focus on measuring. The remainder of this paper discusses: (1) prior work on

Sample Item	**Item**	**Ideas being covered**
	Item 1: Quantitative	
Algorithmic	How many grams of MgO will form if 3.4 g of Mg is burned in an excess of oxygen?	1. Atoms are conserved during chemical reactions. 2. The mass of atoms is constant during a chemical reaction.
Conceptual	If 3.4 g of Mg is burned in an excess of oxygen, will the mass of the product be greater, less, or the same as 3.4 g?	
	Item 2: Qualitative	
Algorithmic	What is the H—C—H bond angle in methane?	1. Electrons repel each other. 2. Molecular geometry is determined by electronic geometry.
Conceptual	Why is the H—C—H bond angle in methane not 90°?	

FIGURE 1. SAMPLE ALGORITHMIC AND CONCEPTUAL OPEN-ENDED TEST ITEMS.

student misconceptions in chemistry, (2) a standardized test for assessing conceptual understanding in chemistry, and (3) approaches instructors might use to measure conceptual understanding of students in their own classes.

Work on Student Misconceptions in Chemistry

Four key references review work on misconceptions that students hold about chemical ideas [6–8]. Each of these reviews focuses on a different aspect of conceptual understanding in chemistry. Gabel and Bunce [2] reviewed work on conceptual understanding because of its effects on problem-solving success. Their review of more than 100 research articles is organized by content areas of student misconceptions. Kracjik's [6] review also examined work on student misconceptions, but focused on teaching models for overcoming student misconceptions. The 24 research articles he reviewed are also organized by content area. Nakhleh [7] reviewed almost 40 articles

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about student misconceptions pertaining to chemistry. Finally, Herron [8] examined some 70 research articles about student misconceptions. He related these to Piaget's stages of cognitive development and its impact on chemistry learning.

Because these reviews are somewhat dated, additional research articles have been identified since 1992 in several research and practitioner journals. The number of new studies (and references) are summarized in Table 1. To give a flavor of what was found in these studies, two of these recent articles are summarized below.

Huddle and Pillay [9] analyzed written responses from 535 college chemistry students to stoichiometry and equilibrium questions. For example, students were asked to solve a limiting-reactant problem in which three reagents react to form three products. Analysis of responses revealed that 91% of the students could balance the equation, 76% could determine the number of moles of each reactant present, 45% could determine the identity of the limiting reactant, and 38% could determine the mass of the products formed. Additional analyses identified two misconceptions:

- Students assume limiting reactant means lowest stoichiometry (or smallest coefficient in the balanced chemical equation).
- Students determine the number of moles of each reactant present and then assume that the reactant with the least moles is the limiting reactant (rather than also examining equation coefficients).

The authors also examined student conceptions related to solving equilibrium problems. Students were asked this question:

When 1.00 mol H_2O is placed in a 50.0 dm^3 container and heated to 1700 K, the equilibrium constant for the reaction:

$$2\,H_2O \rightleftharpoons 2\,H_2 + O_2 \quad \text{is } K_c = 1.35 \times 10^{-11}\ \text{mol dm}^{-3}$$

(i) What does the value of K_c tell you about the position of the equilibrium?

(ii) Calculate the amount of O_2 present at equilibrium. (Hint: Use your answer to (i) to make a reasonable approximation to avoid having to solve a cubic equation.)

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TABLE 1. A Summary of Numbers of Misconception Articles and References Written After 1992 by Content Area in Selected Journals.

Content Area	Reference Numbers
Acid and Bases	14–17
Atoms and Molecules	18–21
Bonding	22
Chemical and Physical Change	23–30
Chemical Symbols	31
Conservation of Matter	24, 25, 32
Electrochemistry	33–35
Energy	36, 37
Equilibrium	38–41
Evaporation and Distillation	42, 43
Gases	10, 44–48
Geometry	49, 50
Light	51, 52
Mass	53
Mole	32, 46, 54—58
Periodicity	24, 25
Solutions	22, 24, 25, 46, 59—62
Stoichiometry	39, 63, 64
Thermodynamics, Heat and Temperature	65—70

Few of the 624 students answered this question correctly. Analysis showed that 29% of the students failed to assume the simplification ($0.020 - 2x \approx 0.020$), 11% applied the assumption incorrectly, and 25% had incorrect stoichiometry. In analyzing the responses, the authors found several misconceptions concerning the simplification step. Student simplifications included:

- $4x^3 = 0$ or $4x^3 = 1$ because x is small
- $K_c = 0$ because K_c is small
- $0.020 - 2x \approx 0$ or $0.020 - 2x \approx 1.00$

Additional analysis of responses showed stoichiometry errors due to students not relating moles of water to moles of H_2 and O_2 produced.

As a second example of recent research on student misconceptions, DeBerg administered a paper-and-pencil test about various properties of gases to 101 high school students [10]. Students were asked qualitative and quantitative questions (see Figure 2 for the qualitative item), and made errors that may surprise chemistry instructors. For the qualitative item, analysis showed that 66% of the students responded correctly to the volume question, 62% to the mass question, and 83% to the pressure question.

The two studies summarized above, along with the numerous references listed in Table 2 show that a wide variety of research has been done on student misconceptions. These research articles can be useful resources for ideas about teaching for and measuring student understanding of chemical concepts.

A Standardized Test of Conceptual Understanding in General Chemistry

In 1994 the ACS Examinations Institute began development of a general chemistry examination focusing on measuring student understanding in general chemistry. The examination was field-tested in 1995 and released for sale in January of 1996. The 60-item, 100-minute exam is intended for use with students that are completing their first year of college chemistry (or an AP high school course). Table 2 shows that the content areas covered by the exam are the same as those found in the traditional first-year ACS examination.

The committee worked to develop items in these traditional areas that were of a conceptual rather than algorithmic nature. Several types of items were constructed, including: (1) pictorial items focusing on the particulate nature of matter, (2) linked questions in which a prediction was asked in one item and an explanation for the prediction in the next, and (3) laboratory questions. Draft example items (that do not appear in the published exam) are shown in Figure 3 for each of these types of questions.

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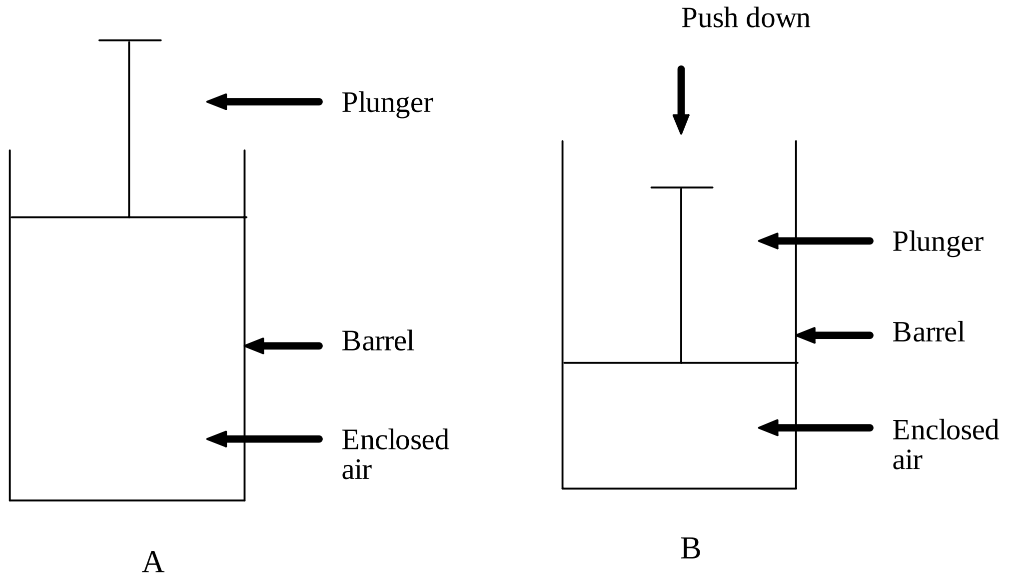
The following diagram represents a sealed syringe in two situations, A and B. In situation B, the plunger has been pushed down the barrel of the syringe without any air leaking into or out of the barrel.



For each of the three questions below, tick the box beside the *one* answer you think is correct.

(i) What happens to the *volume* of the air?

the volume of enclosed air in A is *greater* than the volume of enclosed air in B ☐

the volume of enclosed air in A is *less* than the volume of enclosed air in B ☐

the volume of enclosed air in A is the *same* as the volume of enclosed air in B ☐

(ii) What happens to the *mass* of the air?

the mass of enclosed air in A is *greater* than the mass of enclosed air in B ☐

the mass of enclosed air in A is *less* than the mass of enclosed air in B ☐

the mass of enclosed air in A is the *same* as the mass of enclosed air in B ☐

(iii) What happens to the *pressure* of the air?

the pressure of enclosed air in A is *greater* than the pressure of enclosed air in B ☐

the pressure of enclosed air in A is *less* than the pressure of enclosed air in B ☐

the pressure of enclosed air in A is the *same* as the pressure of enclosed air in B ☐

FIGURE 2. ITEM ASKED AS PART OF THE DEBERG STUDY.

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TABLE 2. Content Areas Covered by the General Chemistry (Conceptual) Exam Available from the ACS Examinations Institute

Content Areas
States of Matter
Stoichiometry–Thermochemistry
Atomic Structure–Periodicity
Molecular Structure
Solutions
Chemical Equilibrium–Molecular
Acid-Base–Ionic Equilibrium
Kinetics
Thermodynamics
Electrochemistry–Redox
Descriptive Chemistry

The research results on student misconceptions presented in the last section of this article served as one source of ideas for the test items used on the ACS General Chemistry (Conceptual) Examination. While generating distracters for quantitative items is relatively easy (by making the same sorts of errors students would make, i. e., not converting to the Kelvin scale when solving many types of gas law problems or forgetting to take the log or antilog when solving pH questions), generating plausible distracters for explanations requires the collection of student misconceptions through analysis of responses to free-response items in writing or through interviews. The research studies reported in this paper provide a compendium of misconceptions students have about various chemical concepts, and they can serve as a source for distracters in multiple-choice conceptual items.

Writing Conceptual Items for the Classroom

Given that conceptual understanding is a valued learning outcome for general chemistry students, we should try to assess it in our students. The research on student misconceptions shows that there are many areas in which students have problems, and

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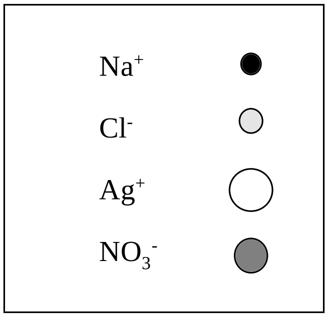
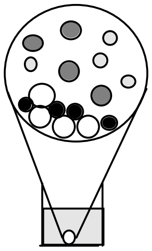
Sample Item

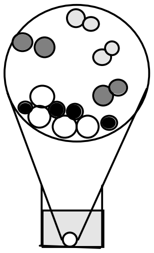
Particulate Sample Item

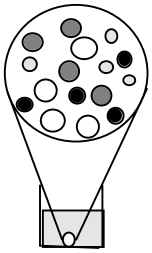
Suppose aqueous solutions of silver nitrate and sodium chloride are mixed. The ions in the initial solutions are depicted as follows:

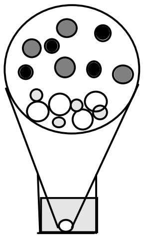


Which diagram below best represents the contents of a beaker in which the two solutions are mixed (water molecules are not shown)?


A


B


C


*D

Linked Sample Item

1. A child blows up a balloon to a volume of about 2 L. What happens to the volume of the gas if the balloon is put in a freezer? The volume is

A. the same as the original volume.

*B. less than the original volume.

C. greater than the original volume.

D. impossible to determine.

FIGURE 3. SAMPLE CONCEPTUAL ITEMS.

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2. What is the reason for your answer to #1?

The molecules of gas

A. get smaller when they get cold.
B. expand when they are cooled.
C. are not affected by temperature changes.
*D. have a decreased amount of kinetic energy.
E. have an increased amount of kinetic energy.

Laboratory Sample Item

Which procedure would effectively separate sugar from a mixture containing the solids alum, sugar, and sand if their solubilities in three solvents are as follows:

	Solvents		
Substances	**Water**	**Ethanol**	**Hexane**
alum	soluble	insoluble	insoluble
sugar	soluble	soluble	insoluble
sand	insoluble	insoluble	insoluble

A. Add water to the mixture, stir and filter, then dry the solid remaining on the filter paper.
B. Add ethanol to the mixture, stir and filter, then dry the solid remaining on the filter paper.
C. Add hexane to the mixture, stir and filter, then dry the solid remaining on the filter paper.
D. Add water to the mixture, stir and filter, then evaporate the filtrate from the beaker.
*E. Add ethanol to the mixture, stir and filter, then evaporate the filtrate from the beaker.

FIGURE 3. SAMPLE CONCEPTUAL ITEMS (CONTINUED).

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the ACS General Chemistry (Conceptual) Examination is one example of a test for measuring student conceptual understanding. Still, how can instructors assess conceptual understanding in their own classes on a regular basis so that instruction can be modified to overcome some student misconceptions? Three responses to this question are given below that might prove helpful in both small and large-class settings.

Review the Literature on Misconceptions

Because of the extensive nature of the research available on student misconceptions in chemistry, it would be useful to read several articles in one or two of the content areas that will be covered during a course. The references provided serve as a useful starting point. In reading the articles it might be helpful to list: (1) misconceptions that are identified for the content area, and (2) questions used in the article that might be used in the class. These articles can serve as a source for distracters for multiple-choice items, open-ended questions, and in-class discussion questions.

Use Open-Ended Questions

In small classes it can be fairly easy to use open-ended questions because grading is not too time consuming. Even in larger classes (say greater than 100 students), open-ended questions can often be used when instructional support is available in the form of teaching assistants or graders. The sorts of items shown in Figure 4 can be used as a source for identifying student misconceptions. In turn, the misconceptions identified in the local student population can then be converted into multiple-choice items on future tests where the identified misconceptions can be used as distracters.

Use In-Class Think-Aloud Pairs

This approach is particularly well-suited to midsized classes, or to large classes with no instructional support, because a broad range of misconceptions will emerge. Identify two or three concepts that are being covered during a week. Develop two open-ended items that might be used for determining whether students have attained the concept (see Figure 5 as an example, [11]). Put one item on the front and the second item on the back of a single page. During lecture, distribute the questions and have students pair up. Ask pairs to do the following during a 10-minute period.

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Topics		**Item**
Atoms, molecules, atomic structure	1.	Using a sketch, and describing in words, show similarities and differences between a sodium ion and a sodium atom. Be sure to include appropriate numbers of electrons, protons, and neutrons, and their relative sizes and locations.
Physical and chemical changes	2.	Using a sketch, and explaining in words, describe similarities and differences between water boiling and water being decomposed to form oxygen and hydrogen. In your sketch be sure to indicate what chemical species are present and the relative distances between them.

FIGURE 4. EXAMPLE OF OPEN-ENDED ITEMS.

1. Have one student think aloud while answering the first item. The second student is assigned a listening role.
2. After the first student finishes the first item, the second student should ask questions about the solver’s reasoning.
3. Turn the page over and switch roles.

Collect the students’ responses and examine them for various types of misconceptions. The identified misconceptions can be addressed during additional instruction, and/or used as a source for test items. The student interaction has the added benefit of enhancing achievement [12] and reducing misconceptions [13].

Conclusions

Given that understanding of chemical concepts is a valued learning outcome for the chemistry teaching community, it is an outcome that needs to be measured so instructors can modify student misconceptions. The extensive research on chemical misconceptions can be a useful starting point for instructors to use for assessing their own students’ misconceptions. Instructors might also consider using the General Chemistry (Conceptual) Examination, available from the ACS Examinations Institute, as a measure of how well their students are thinking conceptually.

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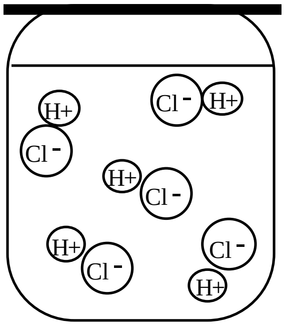
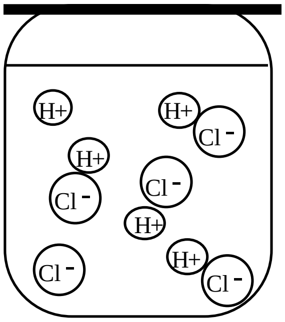
Item

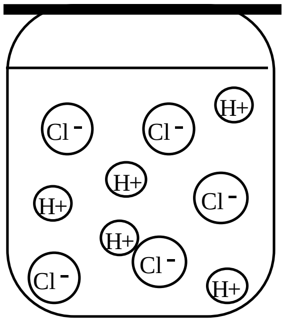
1. Hydrochloric acid, HCl, is considered a strong acid. Which microscopic representation best illustrates this concept?



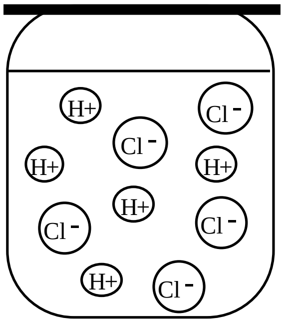
(A)



(B)



(C)

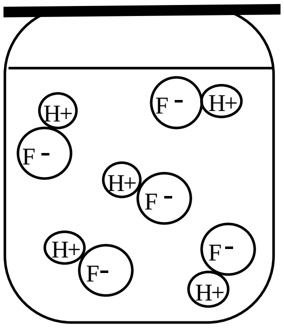


(D)

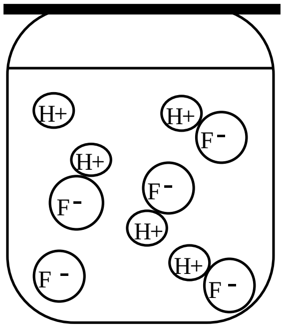
Why?

Please Turn Over

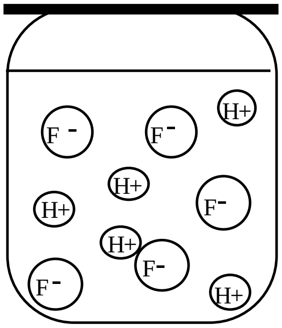
2. Hydrofluoric acid, HF, is considered a weak acid. Which microscopic representation best illustrates this concept?



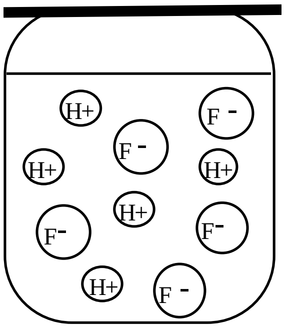
(A)



(B)



(C)



(D)

Why?

FIGURE 5. EXAMPLE ITEMS FOR IDENTIFYING MISCONCEPTION BY THINK-ALOUD PAIRS.

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