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A Performance-Based Assessment for Limiting Reactants

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ABSTRACT: Educators are increasingly being called upon to provide evidence of student learning. Traditional assessments are not always the best venue for demonstrating conceptual understanding, particularly in science. This paper presents details on the design, use, and scoring of a performance-based assessment for measuring student understanding of limiting reactants. The authors encountered a variety of challenges in the process of designing the performance-based assessment; these are described as well.

KEYWORDS: First-Year Undergraduate/General, Chemical Education Research, Demonstrations, Laboratory Instruction

In this paper, we describe a performance-based assessment tool that measures student conceptual understanding of the role of reactants in chemical reactions. While others have used classroom demonstrations in combination with assessment, the system presented here provides opportunities for group discussion and collaboration.[1] In addition, this assessment tool measures the student's ability to use evidence to support an argument or claim, a current focus of science education reform and research.

Science educators increasingly perceive the science laboratory as a unique learning environment in which students may learn and practice skills that have a broad application.[2] The science laboratory offers a varied learning environment in which students may not only develop their understanding of scientific concepts, but may also engage in the process of constructing knowledge by doing science.[3] As the goals for the science laboratory shift toward providing authentic science experiences, so should the tools used to measure student learning.

To measure reform effectiveness, educators and researchers have begun to use alternative assessments. Alternative assessment means any assessment format that is nontraditional, usually requiring student construction, demonstration, or performance. Such alternative assessment tools are designed to measure higher-level cognitive skills, such as problem solving, inquiry, communication, and argumentation as well as understanding of content.[4] In addition, performance-based assessments connect and interface with the NSES,[5] which argue that the content and form of a performance-based assessment must be congruent with that which is being measured. The NSES further argue that assessment tasks that are similar in form to tasks in which students will engage in their lives outside the classroom or are similar to the activities of scientists are "authentic" and therefore more valid.[5] While the NSES are written for K−12 education, their application in undergraduate education is seen in expanding methods of instruction coupled with alternative assessments, such as concept mapping, journals, portfolios, and performance-based assessments that require students to evaluate situations.[6]

Common chemical demonstrations are easily adapted for performance-based assessments that can capture not only students' conceptual understanding, but their ability to use evidence and reasoning as well. We developed such a performance-based

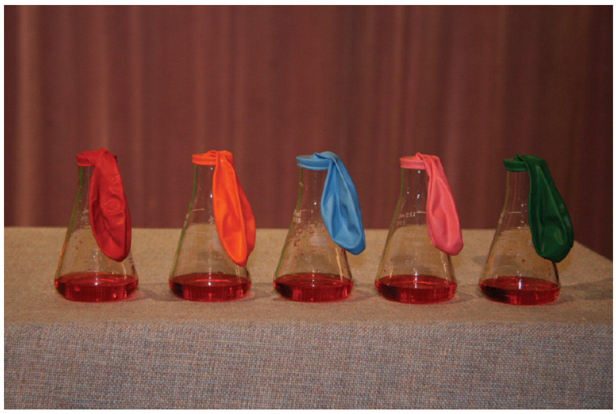

Figure 1. Flasks and balloons before reaction.

assessment to evaluate student understanding of limiting reactants based on the Balloon Race demonstration.[7] This demonstration, as written, mixes constant volumes of 1 M acetic acid with increasing amounts of sodium bicarbonate added from a balloon covering the mouth of a flask. There are six reactant combinations that progress from sodium bicarbonate being limiting, to stoichiometric amounts of reactants, to acetic acid being limiting. The balloons inflate to different volumes based on the amount of sodium bicarbonate they contained. The demonstration nicely illustrates that the amount of product will increase with increasing amounts of reactant, but not indefinitely. The last three balloons inflate to the same size and in the last two flasks there is clearly unreacted sodium bicarbonate solid. As an additional variable, we added universal indicator to the flasks and for expedience we reduced the number of reaction flasks to five.

■ PROCEDURE

We wanted students to be able to interact with materials directly, but also maintain some control over the results, so we prepared group sets of five balloon-covered flasks. Each group of

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Table 1. Balloon Race Flask Set

Flask	Balloon Color	Volume of 1 M $HC_2H_3O_2$	Mass of $NaHCO_3$, g	Mole Ratio of $HC_2H_3O_2$:$NaHCO_3$
1	Red	25.0 mL	0.700	1:0.33
2	Orange	25.0 mL	1.00	1:0.5
3	Blue	25.0 mL	2.10	1:1
4	Pink	25.0 mL	4.20	1:2
5	Green	25.0 mL	6.30	1:3

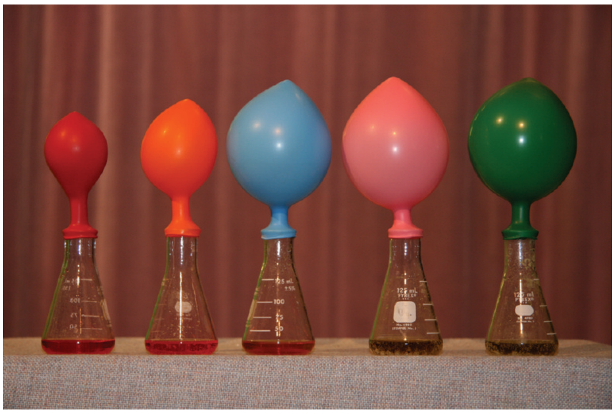


Figure 2. Flasks and balloons after reaction.

four or five students had a set of balloon-covered flasks (Figure 1). They shook the sodium bicarbonate from the balloon into the flask and observed the reaction: the inflating of the balloon and the color change of the solution. The students were then allowed to discuss the experiment for several minutes before being asked to complete the written assessment.

We prepared 40 sets (200 flasks) over a 2-day period for use in 10 lab sections. With two people working in an assembly line, the preparation time was minimized. The details for each flask are provided in Table 1. One timesaving trick was to add the universal indicator to the bulk 1 M acetic acid, 15 mL/L of diluted acetic acid, rather than dropwise to the individual flasks. The various levels of inflation are most apparent with nine-inch balloons (Figure 2).

The answer sheet (Figure 3) for the assessment provided general information about the reaction and asked the students to identify the limiting reactant in each flask, to provide evidence for this conclusion, and to use this evidence to illustrate their reasoning. The answer sheet repeated the blocked section five times and provided more space for evidence and reasoning. The scoring rubric is provided as Table 2. The evidence for each flask was generally solution color, balloon inflation size, and presence of solid residue. Each of these variables could then be used to illustrate a student's choice for limiting reactant.

CHALLENGES

We had to make several changes to our original design before a successful system was developed. The problems we encountered are worth documenting both to prevent repeating by others and to illustrate unexpected issues that may arise in developing a performance-based assessment. In the first iteration of the assessment, we used four balloons numbered 1−4 and an answer sheet with space for observations and two opened-ended questions (Figure 4). The same header information was provided as in Figure 3. This design was not useful for eliciting the students' explanations about the chemical processes for several reasons. The students focused on the numbers on the balloons as evidence for reactant level rather than the color change, balloon inflation size, or unreacted solid material. The open-ended questions required students to assimilate too much information into a single statement, so their answers were nonsensical at best. We were perplexed by the fact that only two students mentioned the excess sodium bicarbonate in the fourth flask; however, when presented with the same system, faculty missed the excess reactant as well (Figure 5). We realized that the foaming bubbles were obscuring the solid residue and that given time the bubbles dissipated and the solid on the bottom was visible.

The four balloons were designed to show increasing levels of CO_2 for Flasks 1−3 then level off with Flask 4. However, based on their responses, the students and the faculty assumed that the increase had continued even for Flask 4. To address these issues, we broke the answer sheet into individual questions for each flask, used balloons to color code the flasks, and added a fifth flask to more clearly establish the leveling off of CO_2 production. We also suggested to students that they swirl the flasks to dissipate the bubbles.

Limiting and Excess Reactants

Each of the flasks contains the same amount of acetic acid ($HC_2H_3O_2$) and each balloon contains a different amount of sodium bicarbonate ($NaHCO_3$). There is an acid/base indicator which will change from red (acid is present) to green (if no acid is present). The chemical reaction that occurs is given below.

$$HC_2H_3O_{2(aq)} + NaHCO_{3(s)} \rightarrow CO_{2(g)} + H_2O_{(l)} + NaC_2H_3O_{2(aq)}$$

Balloon Color: ______________

Is the Limiting Reactant: $HC_2H_3O_2$ or $NaHCO_3$ or Neither? (circle one)

How do you know? Defend your explanation with appropriate evidence and reasoning.

The evidence is…

The reasoning is…

Figure 3. Condensed student answer sheet.

EXAMPLES OF STUDENT WORK

The performance-based assessment presented in this paper provided an excellent system for evaluating the students' understanding of the limiting reactant concept. When the assessment was administered following the laboratory investigation on limiting reactants in chemical reactions, student scores ranged from 0 to 26, indicating a wide range of conceptual understanding. The students with the zero scores were not even able to discern the limiting reactant. Many students insisted that they needed to know the mass of sodium bicarbonate and use a calculator to find the limiting reactant. Examples of student answers for two of the five balloons are provided in Figure 6. The score for the pink balloon would be 5 points: 1 point for correctly identifying the limiting reactant, 2 points for the evidence, and 2 points for the reasoning. The student used solution color and the presence of solid residue as evidence and then further explained both in his or

Table 2. Scoring Rubric

Ratio of Reactants	Answer—1 point each item	Points
1 to 0.33		
Limiting Reactant	$NaHCO_3$	/1
Evidence	The solution is red; The balloon barely inflated; There is no solid left in the flask	/3
Reasoning	The color indicates that acid is still present; The solid is entirely used up so the solid is limiting; The small balloon indicates that more reaction is possible	/3
1 to 0.5		
Limiting Reactant	$NaHCO_3$	/1
Evidence	The solution is reddish/pink; The balloon is second smallest or bigger than the red balloon; There is no solid left in the flask	/3
Reasoning	The color indicates that acid is still present; The solid is entirely used up so the solid is limiting; The small balloon indicates that more reaction is possible	/3
1 to 1		
Limiting Reactant	Neither	/1
Evidence	The solution is orange; The balloon is maximum size; There is no solid left in the flask	/3
Reasoning	The color indicates all the acid has been used; The solid is entirely used up so the solid is not in excess; The size of the balloon indicates that all the acid is used up	/3
1 to 2		
Limiting Reactant	$HC_2H_3O_2$	/1
Evidence	The solution is green; The balloon is the same size as the blue and orange balloons; There is solid left in the flask	/3
Reasoning	The color indicates excess base; The solid left in the flask indicates excess base; The size of the balloon indicates that all the acid is used up	/3
1 to 3		
Limiting Reactant	$HC_2H_3O_2$	/1
Evidence	The solution is green; The balloon is the same size as the blue and orange balloons; There is solid left in the flask	/3
Reasoning	The color indicates excess base; The solid left in the flask indicates excess base; The size of the balloon indicates that all the acid is used up	/3
Total		/35

What do you observe for each of the four reactions?

Flask #	Observation
1	
2	
3	
4	

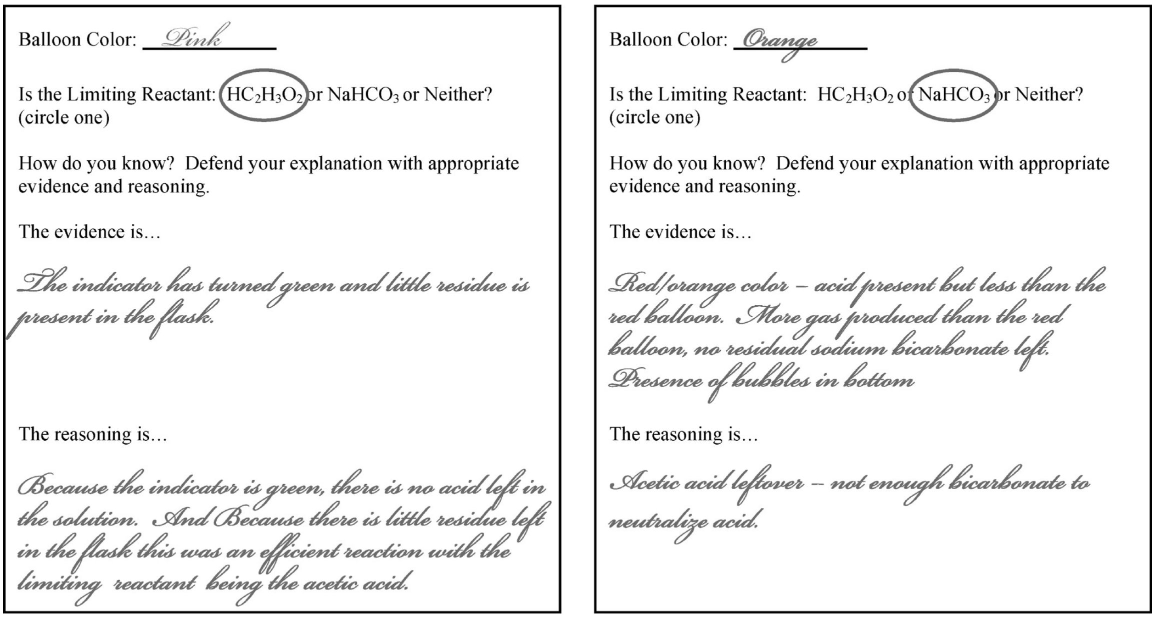
1. How would you explain these observations? In the space below, provide an explanation that includes terms such as limiting and excess reactant.

2. How do you know that your explanation is valid and acceptable? In the space below, use appropriate evidence and reasoning to justify the explanation you provided.

Figure 4. First attempt at an answer sheet.

Figure 5. Unreacted sodium bicarbonate in the fifth flask.

her reasoning. The score for the orange balloon would be 5 points: 1 point for correctly identifying the limiting reactant, 3 points for the evidence, and 1 point for the reasoning. The student used solution color, presence of solid residue, and balloon inflation size as evidence; however, the reasoning only incorporates the excess acid as indicated by the solution


Balloon Color: Pink

Is the Limiting Reactant: $HC_2H_3O_2$ or $NaHCO_3$ or Neither?
(circle one)

How do you know? Defend your explanation with appropriate evidence and reasoning.

The evidence is…

The indicator has turned green and little residue is present in the flask.

The reasoning is…

Because the indicator is green, there is no acid left in the solution. And Because there is little residue left in the flask this was an efficient reaction with the limiting reactant being the acetic acid.

Balloon Color: Orange

Is the Limiting Reactant: $HC_2H_3O_2$ or $NaHCO_3$ or Neither?
(circle one)

How do you know? Defend your explanation with appropriate evidence and reasoning.

The evidence is…

Red/orange color – acid present but less than the red balloon. More gas produced than the red balloon, no residual sodium bicarbonate left. Presence of bubbles in bottom

The reasoning is…

Acetic acid leftover – not enough bicarbonate to neutralize acid.

Figure 6. Examples of student answers for two balloons.

color. The "presence of bubbles" was not relevant and was not scored.

CONCLUSION

In the first semester of general chemistry, the impact of reactant quantity on the products of a reaction is explained in terms of limiting and excess reactants. This concept typically involves time-consuming calculations that students learn algorithmically, often with little understanding of the results. We have found the use of the Balloon Race performance-based assessment to be a better measure of student conceptual understanding of the impact of reactant quantity in chemical reactions. This activity was used as an assessment in a larger research project, so we stopped student discussion after several minutes. This required some effort as the students were engaged in a heated debate over the results and evaluating the meaning of the different factors. This experience suggests that an alternative use of this assessment could be as a group activity that would allow for authentic argumentation.

Performance-based assessment offers a means for attaining insight into student conceptual understanding as well as providing an alternative venue for student learning. This paper has presented an example of how educators can develop performance-based assessments from simple demonstration activities.

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