Good Practice Report

Khaled W. Omari* and Jestin B. Mandumpal

A simple pedagogical limiting reactant kitchenette experiment including a simple algorithm

https://doi.org/10.1515/cti-2022-0028
Received October 10, 2022; accepted March 26, 2023; published online April 20, 2023

Abstract: Limiting reactants is a crucial factor in any reaction. Students found it a tricky topic. The current study has intended to conduct a kitchenette experiment, in which a student will follow the instructional procedure to determine a limiting reactant in a self-learning process. The study has adopted an experimental approach. A program was developed in C++ as an efficient tool to determine the limiting reactant. The major outcomes drawn from the study have enlightened the significance of a balanced equation in obtaining the correct molar ratio. It has also been noted that molar ratio similarity in a particular balanced equation can wrongly lead to an erroneous assumption.

Keywords: algorithm; freshman/sophomore (age group 18–20); kitchenette experiment; limiting reactant.

1 Introduction

Limiting reactants is a challenging topic for beginners in chemistry. Having a simple kitchenette experiment including theoretical calculation can help students better understand this topic in a practical-theoretical inexpensive way. Sodium bicarbonate (baking soda, $NaHCO_3$) and acetic acid (vinegar, CH_3COOH) were used as reactants in this approach. $NaHCO_3$ is a benign chemical (Fiore & Calabrese, 2019) for environmental and human health concerns and is used as an antacid agent in medicinal drugs. Sodium bicarbonate is commercially available and called baking soda. At oven baking temperature (180 °C), it decomposes to produce carbon dioxide (CO_2). CO_2 is a leavening agent (Brodie & Godber, 2007) that helps dough aeration to rise to have a porous cell structure for nice-looking baked goods. It is a cheap and readily available substance used in food stores and most kitchens.

$NaHCO_3$ reacts with acetic acid (CH_3COOH) (Arieff, 1991) to produce a salt (CH_3COONa) and carbonic acid (H_2CO_3) (Johnston & Gaas, 2006). However, the decomposition rate of this substance is very high. Therefore, it will be immediately decomposed to form CO_2 and water (H_2O). Acetic acid is one of the simplest forms of organic acids. It has been used in many fields such as food since 5000 B.C. (Fordtran et al., 1984). Acetic acid at a particular concentration is used in food and is called vinegar. There is a high production rate of CH_3COOH (ca. 1.83 megatons worldwide) (Freer et al., 2003). There are numerous ways by which CH_3COOH can be produced, e.g., using bacteria. For example, ethanol fermentation using yeast and glucose fermentation using thermophilic Clostridium spp. are processed to yield CH_3COOH. In concept, acetic acid bacteria oxidize sugar into CH_3COOH (Jia et al., 2017).

Understanding mole concepts and stoichiometric coefficient (JCE Staff, 1997) are crucial for limiting reactant topic gain. Several published articles discussed limiting reactant topics as they are complicated based on students'

***Corresponding author: Khaled W. Omari**, College of Engineering and Technology, American University of the Middle East, Kuwait, E-mail: khaled.omari@aum.edu.kw. https://orcid.org/0000-0002-3089-2893
Jestin B. Mandumpal, College of Engineering and Technology, American University of the Middle East, Kuwait

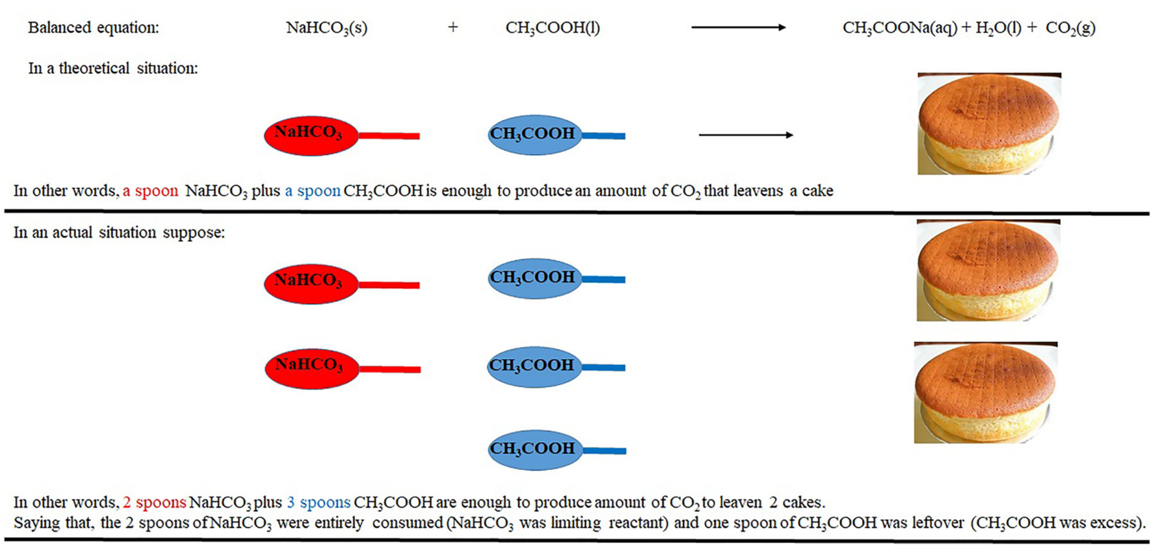

Figure 1: A reaction illustrating A limiting reactant that yields CO_2 (a cake-leavening agent).

feedback (Blankenship, 1987; Chen & Yaung, 2002; González-Sánchez et al., 2014; Kalantar, 1985; Kashmar, 1997; Ozsogomonyan, 1979; Phillips, 1994; Tóth, 1999). In this article, the following simple reaction (see Equation (1)) was used to determine limiting reactants in students' self-learning approach. Students can perform it as a kitchenette experiment.

$$NaHCO_{3(s)} + CH_3COOH_{(aq)} \rightarrow CH_3COONa_{(aq)} + H_2O_{(l)} + CO_{2(g)} \tag{1}$$

The advent of computers enabled learners to incorporate software and computer programs into learning. One aspect of computing is to use mathematical descriptions to demonstrate theories (Schwarz et al., 2013). C++ program has been developed in order to support experimental procedures. This article will help freshman/sophomore (age group 18–20) students understand limiting reactants using plain language as preparation for this topic.

In Figure 1, the limiting reactant concept in this article is depicted in which the products in the previous reaction yielded CO_2, which is considered enough to leaven a cake.

2 Experimental section

For safety precautions, see the Supplementary Information S1.

2.1 Materials and equipment

The necessary materials and equipment to perform the experiment are as follows. Baking soda (sodium bicarbonate, $NaHCO_3$) is commercially available in a food store. Vinegar (acetic acid, CH_3COOH) is commercially available in a food store. Teaspoon (spatula in a laboratory language), commercially available at tableware store. Small glass cup (ca. 3–5 ounces or ca. 90–150 mL), commercially available at tableware store. Kitchen balance of two decimal places capability, commercially available at the electronics store—a piece of paper, 3 × 3 cm.

2.2 Procedure

The objective of experimenting is to determine the limiting and excess reactants. Two cups were marked (A and B). In a glass cup, 2.0 g of vinegar was weighed. 0.2 g of baking soda was weighed and transferred over the vinegar on a weighing paper. This cup was marked (A) and repeated in the same manner in another cup (B). Effervescence was observed, and both cups were swirled until no gas was given off. On another weighing paper, 0.1 g of baking soda was weighed and added to cup (A). In a third glass cup, 1.0 g of vinegar was weighed and transferred to cup (B). However, effervescence was started in cup (A) but not in cup (B).

3 Results and discussion

The contents in cups A and B were initially the same. Vinegar content (CH_3COOH) was reacted with baking soda ($NaHCO_3$) to produce CO_2, which was noticed as bubbling in the solution (effervescence, chemical change). Once the effervescence was stopped, indicating that either vinegar or baking soda was entirely consumed, and the other had leftovers. To test which one was finished and which one had leftover. The effervescence was restarted after adding 0.1 g $NaHCO_3$ that reacted with the leftover vinegar. Consequently, the leftover was the CH_3COOH. As a result, $NaHCO_3$ is the limiting reactant.

3.1 Theoretical calculations

In chemistry, reactions are quantified in terms of number of moles of each substance in which moles of $NaHCO_3$ reacted with moles of CH_3COOH (moles, not grams). Therefore, if a limiting reactant cannot be tested experimentally for any reason, theoretical calculations can help determine the limiting reactant. In estimations, colour codes were used to differentiate similar values from one another based on their particular theoretical calculation depending on molar ratios (stoichiometric coefficient in a balanced equation).

A balanced equation representing a reaction shall be obtained (see the balanced chemical reaction in the introduction). In this equation, the molar ratio among reactants and products is 1:1. Other balanced chemical equations could have a different molar ratio, e.g., 3:1. Moles of every reactant should be calculated. In this experiment, $NaHCO_3$ was assumed to be pure, i.e., it contains 0.2 g $NaHCO_3$. For CH_3COOH, it was assumed that the amount (grams) of CH_3COOH in vinegar was 0.5 g (commercial vinegar is available as ca. 5 %w/w CH_3COOH).

$$\text{Moles of NaHCO}_3 = 0.2\,\text{g NaHCO}_3 \times \frac{1\,\text{mol NaHCO}_3}{84.01\,\text{g NaHCO}_3} = 0.002\,\text{mol NaHCO}_3 \quad (2)$$

$$\text{Moles of CH}_3\text{COOH} = 0.5\,\text{g CH}_3\text{COOH} \times \frac{1\,\text{mol CH}_3\text{COOH}}{60.06\,\text{g CH}_3\text{COOH}} = 0.008\,\text{mol CH}_3\text{COOH} \quad (3)$$

The calculated amount (moles) of a product using the first reactant and the same product using the second reactant were shown as follows.

$$\text{From NaHCO}_3\text{, moles of CH}_3\text{COONa} = 0.002\,\text{mol NaHCO}_3 \times \frac{1\,\text{mol CH}_3\text{COONa}}{1\,\text{mol NaHCO}_3} = 0.002\,\text{mol CH}_3\text{COONa} \quad (4)$$

$$\text{From CH}_3\text{COOH, moles of CH}_3\text{COONa} = 0.008\,\text{mol CH}_3\text{COOH} \times \frac{1\,\text{mol CH}_3\text{COONa}}{1\,\text{mol CH}_3\text{COOH}} = 0.008\,\text{mol CH}_3\text{COONa} \quad (5)$$

The limiting reactant produces a lower amount (moles) of the product (limit the amount of the product). In this case, the limiting reactant was $NaHCO_3$ as per (4) compared to (5) and was CH_3COOH excess. This result was in-line with the experimental observations.

Table 1: Reaction table for $NaHCO_3$ and CH_3COOH reaction introduced in this case study.

Moles	Balanced equation				
	$NaHCO_{3(s)}$ +	$CH_3COOH_{(aq)}$ →	$CH_3COONa_{(aq)}$ +	$H_2O_{(l)}$ +	$CO_{2(g)}$
Initial	**0.002**	**0.008**	0	0	0
Change	−**0.002**	−**0.002**	+**0.002**	+**0.002**	+**0.002**
Final	0	+0.006[a]	+0.002	+0.002	+0.002

[a]Remaining amount (leftover, moles) of CH_3COOH after the reaction completion.

3.2 Reaction table

A reaction table is a table that summarizes the reaction in its steps. The steps are initial (before starting the reaction, i.e., before mixing the reactants together), change (while mixing the reactants together), final (after the reaction is done). The following reaction table, Table 1, described $NaHCO_3$ and CH_3COOH reactions in this case study.

In Table 1, the initial amount (moles) of $NaHCO_3$ was 0.002 mol which was reacted in this case study. Well, knowing that $NaHCO_3$ is the limiting reactant, from its definition, the amount (moles) of the limiting reactant was entirely consumed in the reaction. As a result, its change was the same amount (moles) (0.002), and the sign is negative because it was consumed. After the reaction is done, the final amount (moles) showed zero because of the total consumption, i.e., initial + change = (0.002) + (−0.002) = 0. For the other reactant (CH_3COOH), the reaction was started with 0.008 mol. Initially, the reaction had 0.008, and the change in moles of CH_3COOH was calculated using limiting reactant amount (moles), which controlled the reaction as follows.

$$\text{Change in moles of } CH_3COOH = 0.002\,\text{mol}\,NaHCO_3 \times \frac{1\,\text{mol}\,CH_3COOH}{1\,\text{mol}\,NaHCO_3} = 0.002\,\text{mol}\,CH_3COOH \quad (6)$$

Therefore, the change for this reactant is −0.002 mol, see (7). The final amount (CH_3COOH, moles) was (0.008) + (−0.002) = +0.006. For CH_3COONa, initially, there was no product (zero mole product) because the reactants had not yet been mixed. This case also applied for the other two products (CO_2 and H_2O). The change in its amount (moles) was calculated based on the initial amount (moles) of the limiting reactant, see (3). Consequently, the final amount (moles) was the sum of the initial amounts (moles) and the change to be +0.002. For H_2O and CO_2, both substances initially had no moles. Both were produced in a change, and the limiting reactant, $NaHCO_3$, limits their amounts (moles) yielded (see (6) and (7)). The calculation based on the limiting reactant is shown as follows.

$$\text{Moles of } H_2O = 0.002\,\text{mol}\,NaHCO_3 \times \frac{1\,\text{mol}\,H_2O}{1\,\text{mol}\,NaHCO_3} = 0.002\,\text{mol}\,H_2O \quad (7)$$

$$\text{Moles of } CO_2 = 0.002\,\text{mol}\,NaHCO_3 \times \frac{1\,\text{mol}\,CO_2}{1\,\text{mol}\,NaHCO3} = 0.002\,\text{mol}\,CO_2 \quad (8)$$

The change in H_2O is +0.002 mol and +0.002 for CO_2. There will be 0.002 mol produced for each product in the final stage. The final step in Table 1 showed remaining (leftover), moles from the excess reactant, amount (moles) of products, and always zero for the limiting reactant as nothing will remain after the reaction is done. As shown in Table 1, there is no $NaHCO_3$ left in the final stage of the reaction. This matches the limiting reactant's definition, a reactant that is entirely consumed throughout the reaction process. Also, the remaining amount (leftover moles) of CH_3COOH complies with the description of excess reactant. Consequently, if more products need to be yielded, more amounts (moles) of limiting reactant should be added to match the remaining amount (leftover, moles) of the excess reactant, which can be calculated using molar ratio.

$$\begin{aligned}\text{Moles of } NaHCO_3 \text{ to be added to resume the reaction} &= 0.006\,\text{mol}\,CH_3COOH \times \frac{1\,\text{mol}\,NaHCO_3}{1\,\text{mol}\,CH_3COOH} \\ &= 0.006\,NaHCO_3 \quad (9)\end{aligned}$$

3.3 Algorithm

From the definition of the limiting reactant, a computer program (C++) was developed, as illustrated in Figure 2. First, the user supplies the data consisting of reactants and products (formulae) and their masses. Consequently, molar mass was calculated. Using molar coefficients (stoichiometry), the amount of a particular product was determined from each reactant. The limiting reactant was identified as the reactant that produced the lowest amount (mol) of product.

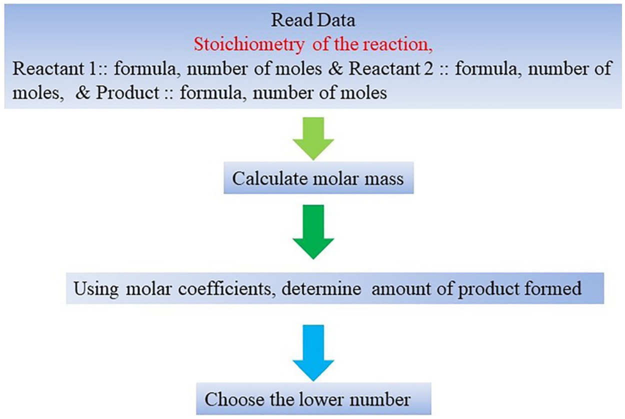

Figure 2: The algorithm to determine the limiting reactant.

The program was written using C++ software. All the main features of C++ were utilized to complete the program. The program was written in a lucid style. Therefore, any updates/modifications are simple to implement. Two input files were required to program it. The list of elements and their atomic masses is a static input. The second one is a dynamic in which information related to reactants/products was specified by a user. In this input file, data such as the number and types of atoms of reactants/products, stoichiometry, and the number of moles were mentioned.

Static Input File: Hundred and eighteen elements were stored in this file to be used later. In the Supplementary Information Table S1 shows an example of contents which are an element, atomic number, and atomic mass.

Dynamic Input File: In the dynamic file, the user-provided all necessary information to compute the number of moles of reactants and one of the products to determine the limiting reactant. Information includes the type of atom and its corresponding mole number. For example, the $NaHCO_3$ formula has 1 mol Na, 1 mol H, 1 mol C, and 3 mol O. Also, the dynamic file includes the experimental moles of reactants and products as shown in the Supplementary Information Table S2, e. g., see Equations (2) and (3) where the experimental moles of $NaHCO_3$ and CH_3COOH were calculated.

The basic stoichiometry part of the code is shown in the Supplementary Information S2 program protocol Figure S1. After the stoichiometric part of the code, the program calculates the conversion of the number of moles of the reactants. This is followed by calculating molar masses which was recalled later in the first part. The number of moles of the products was calculated afterward. The limiting reactant was identified by the code, Supplementary Information S2 program protocol Figure S2.

4 Students' invalid assumptions

We provide examples of how students tend to assume wrong conclusions based on misunderstood observations.

(1) The amount (moles) for $NaHCO_3$ is less than CH_3COOH, the limiting reactant is $NaHCO_3$.
This is an unacceptable assumption since it is only applicable when the molar ratios are 1:1 for the reactants.

(2) Since the amount (moles) for the limiting reactant is 0.002 and the molar ratio of each substance in the balanced reaction is 1:1, the amount (moles) for all other substances in the change in Table 1 are the same. This assumption is correct only in this case. However, when molar ratios are not 1:1, the amounts in mole are not the same.

(3) Generally, a student may assume that the reactant that has the least stoichiometric coefficient is the limiting reactant. For this case study, an assumption could be that both reactants are limiting reactants.
This is an unacceptable assumption because to identify the liming reactant a student should perform the experiment or perform a proper calculation.

(4) A student could start with grams of reactants and use the molar ratio to determine the limiting reactant. In this case study, the experiment started with grams. Grams must be converted into moles before applying molar ratio in the theoretical calculations. Also, it was pointed out that moles of substance are reacted and not grams.

(5) After determining the limiting reactant, a student could think to use either limiting reactant or excess reactant to calculate amount (moles) for any other substance in a reaction.
This is an invalid assumption due to the student's lack of understanding that the liming reactant is the controller for the reaction. Thus, its amount (moles) must be solely used to calculate any other amount of any substance in the reaction.

5 Conclusions

Limiting reactant was pedagogically introduced in a simple experiment, which can be performed in a kitchen where a freshman/sophomore (age group 18–20) student can obtain a basic preliminary understanding of the concept. In this article, theoretical calculations were introduced and discussed, including the reaction table, which summarizes all reaction stages. This article emphasized the importance of a balanced equation to obtain the correct molar ratios included in the calculation to determine limiting reactants and other aspects of the reaction. It is worth mentioning that molar ratios similarity in a certain balanced equation can faultily lead a student toward a wrong conclusion. It is proved to students that no guess can be established based on the amount (moles) of reactants, i.e., it is not always the least initial moles of a reactant is considered a limiting reactant, and it depends on the molar ratios (stoichiometric coefficient in a balanced equation). A code in C++ was developed for the determination of the limiting reactant to support the students who are interested in computer programs. Invalid student's assumption where argued to avoid such suppositions.

Acknowledgment: Calculations have been performed using the Phoenix High Performance Computing facility at the American University of the Middle East, Kuwait. The authors would like to thank Mr. Biju Babu for refining program snapshots.
Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.
Research funding: None declared.
Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

References

Arieff, A. (1991). Indications for use of bicarbonate in patients with metabolic acidosis. *British Journal of Anaesthesia*, *67*, 165–177.

Blankenship, C. (1987). A "nuts and bolts" approach to explain limiting reagents. *Journal of Chemical Education*, *64*(2), 134.

Brodie, J., & Godber, J. (2007). Bakery processes, chemical leavening agents. In *Kirk-othmer encyclopedia of chemical technology*. John Wiley & Sons Inc. https://onlinelibrary.wiley.com/doi/abs/10.1002/0471238961.0308051303082114.a01.pub2.

Chen, Y-H., & Yaung, J-F. (2002). Alka-Seltzer fizzing-determination of percent by mass of $NaHCO_3$ in Alka-Seltzer tablets. An undergraduate general chemistry experiment. *Journal of Chemical Education*, *79*(7), 848.

Fiore, V., & Calabrese, L. (2019). Effect of stacking sequence and sodium Bicarbonate treatment on quasi-static and dynamic mechanical properties of flax/jute epoxy-based composites. *Materials*, *12*, 1363.

Fordtran, J., Morawski, S., Carol, A., Ana, A., & Rector, F. C., Jr. (1984). Gas production after reaction of sodium bicarbonate with hydrochloric acid. *Gastroenterology*, *87*, 1014–1021.

Freer, S., Dien, B., & Matsuda, S. (2003). Production of acetic acid by *Dekkera/Brettanomyces* yeasts under conditions of constant pH. *World Journal of Microbiology Biotechnology*, *19*, 101–105.

González-Sánchez, A., Ortiz-Nieves, E., & Medina, Z. (2014). A hands-on activity incorporating the threefold representation on limiting reactant. *Journal of Chemical Education*, *91*, 1464–1467.

JCE Staff. (1997). How big is the balloon? Stoichiometry using baking soda and vinegar. *Journal of Chemical Education*, *74*(11), 1328A–1328B.

Jia, B., Chun, B., Cho, G., Kim, K., Moon, J., Yeo, S-H., & Jeon, C. (2017). Complete genome sequences of two acetic acid-producing *Acetobacter pasteurianus* strains (Subsp. *ascendens* LMG 1590t and Subsp. *paradoxus* LMG 1591T). *Frontiers in Bioengineering and Biotechnology*, *5*(33), 14. https://doi.org/10.3389/fbioe.2017.00033.

Johnston, C., & Gaas, C. (2006). Vinegar: Medicinal uses and antiglycemic effect. *Medscape General Medicine*, *8*(2), 61.

Kalantar, A. (1985). Limiting reagent problems made simple for students. *Journal of Chemical Education*, *62*(2), 106.

Kashmar, R. (1997). The use of cut-out molecular models on the overhead projector to illustrate stoichiometry and limiting reactants. *Journal of Chemical Education*, *74*(7), 791.

Ozsogomonyan, A. (1979). An application of Gagne's principles of instructional design: Teaching the limiting-reactant problem. *Journal of Chemical Education*, *561*(12), 799.

Phillips, J. (1994). A graphical representation of limiting reactant. *A Graphical Representation of Limiting Reactant Journal of Chemical Education*, *71*(12), 1048.

Schwarz, K., Breitling, R., & Allen, C. (2013). Computation: A new open access journal of computational chemistry, computational biology and computational engineering. *Computation*, *1*, 27–30.

Tóth, Z. (1999). Limiting reactant. An alternative analogy. *Journal of Chemical Education*, *76*(7), 934.

Supplementary Material: This article contains supplementary material (https://doi.org/10.1515/cti-2022-0028).