The Making of a Solution: A Simple but Poorly Understood Concept in General Chemistry

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Abstract: A primary goal in many general chemistry laboratories is to teach students to properly perform dilutions and make solutions. This article presents a simple exercise to test if your students have acquired this ability from their introductory laboratory exercises. Our results indicate that approximately 50% of the students cannot perform this task on their first attempt, but with guidance and additional attempts their success rate improves. Approximately 30% of the students still fail at this task after additional attempts, but this exercise does improve the laboratory technique of all students. Students used a variety of dilution strategies to achieve the same final concentration; but the most common strategy used by the students was the one deemed most logical by the professors.

Background

One of the primary goals of most introductory chemistry classes is to teach students to make dilutions and prepare solutions; however, we rarely *directly* test the student's ability to complete this supposedly simple task. We do test the results of a series of weighting, dilutions, and titrations with unknown samples, but this approach does not pinpoint the source of error in the student's technique. To test our student's ability to make a simple solution, we devised the laboratory exercise described in this article. We will present more than sufficient data to show that colleges need to put more emphasis on solution preparation, specifically on more complex calculations, proper weighing techniques, and dilution skills. To date, only two articles on the making of solutions have appeared in the *Journal of Chemical Education* [1, 2], and none have appeared in *The Chemical Educator*. The few articles in print do not give sufficient details on student performance. Our results strongly indicate that more emphasis should be placed on testing the student's ability to perform proper dilution techniques and make solutions of specified concentration.

Laboratory Approach

This exercise is best used at the beginning or end of the second semester for introductory-level chemistry and is a good preparatory exercise for quantitative analysis. At this point, students *should* have developed the mathematical and laboratory skills to complete this task. We asked students to come to laboratory without prelaboratory reading assignments or exercises. At the beginning of the prelaboratory lecture, students are told that they will be making a solution of specified concentration (i.e., 1.50×10^{-4} M Ca^{2+} solution from $CaCO_3$). We explain why the making of such a solution is important in any scientific career and then the students are given written instructions (provided in the Supporting Materials accompanying this article. A summary of our prelaboratory lecture notes is also provided in this material.) A prelaboratory demonstration of proper dilution techniques is very useful at this point.

Students are provided with the following directions and supplies for making their solutions.

Make a 1.83×10^{-4} M solution of Ca^{2+} given the following glassware options and equipment:

- 1 or 2-, 5-, 10-, 25-mL Class A pipets,
- 10-, 25-, 50-, 100-, 250-, and 500-mL Class A volumetric flasks,
- a balance that weighs to 0.001 g (weigh at least 0.100 g of $CaCO_3$ to three decimal places),
- use 99.4 % pure $CaCO_3$ (dried at 104 °C overnight and stored in a desiccator), and
- 6 M nitric acid (add sufficient acid to yield 1% in each solution, that is, 1 mL nitric acid to 100 mL solution).

At this point we also explain that the solution cannot be made directly (with one weighing and filling of a container), and that a more concentrated solution must first be made and then diluted.

Students are given 30 min to complete their calculations and develop a procedure, but they work individually. The calculations are checked as each student completes them, and, if correct, the student proceeds to the laboratory to make their solutions. If the calculations are not correct, five points are deduced from their final score (50-point basis), hints are given for the proper way to complete the calculation, and the student returns to correctly work the problem. At the end of thirty minutes, we go over the proper calculations for the remaining students, deduct five points from their grade, and allow them to proceed to the laboratory portion of this exercise.

As students make their solutions they bring them to the flame atomic absorption spectroscopy (FAAS) unit for

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Table 1. Percent of the 126 Students in Error for Each Trial

Trial	Percent of Student in Error
1	47.6
2	38.9
3	33.3
4	15.1
5	9.5

Table 2. Improvement in Student Performance as the Week Progressed

Laboratory Meeting Day	Percentage of Students in Error – Trial 1
Monday	62.1
Tuesday	45.8
Wednesday	51.2
Thursday	20.8

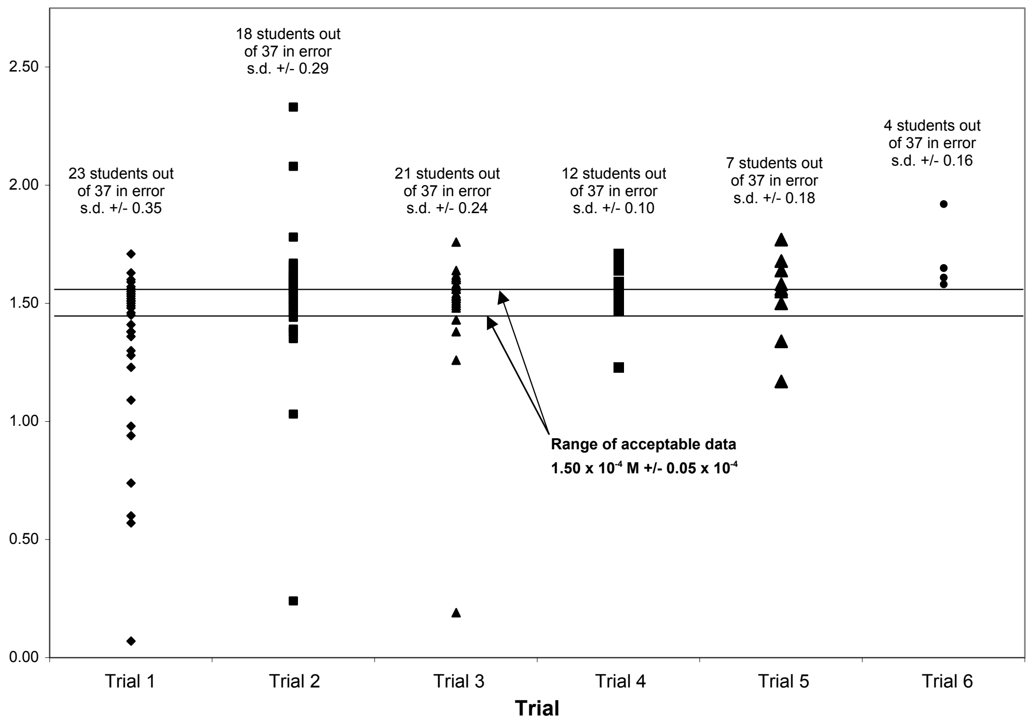

Figure 1. Summary of results for 37 students asked to make a 1.50×10^{-4} M solution of Ca^{2+}.

measurement. Because the students do not have experience in using the FAAS unit, and given the time limitations, an instructor or a laboratory assistant analyzes the solutions for them and explains details of FAAS theory. (The operation and basic theory of the FAAS was explained in the prelaboratory lecture and an analogy was made to the Spectronic 20 that they used earlier in the year.) If a solution of proper concentration has been made by the student, the solution is disposed of and the student is instructed to complete the task two more times to evaluate their precision. They must then calculate the average and standard deviation for their samples that are within the acceptable concentration range. The student must hand in all calculations and their data sheet (supplied with the Supporting Materials). If the concentration is incorrect, five points are deducted from the student's grade, and we look for possible sources of error. The student then repeats the exercise until they have three correct solutions or until the laboratory time has expired. Students typically complete the entire laboratory exercise within the standard three-hour time limit.

Materials and Supplies

Chemicals: A reference Ca atomic absorption standard (1000 mg L^{-1}) made from the same $CaCO_3$ used by the students. $CaCO_3$ primary reference, dried at 104 C overnight, 1 g per student. ~6 M ACS-grade concentrated nitric acid.

Instruments: A Ca AAS hollow cathode lamp. A FAAS unit. A Perkin-Elmer 1100B was used in these experiments.

Observations

The introductory chemistry class of 2000, containing 126 students, was evaluated with this exercise. Typical results are shown in Figure 1 (37 students) and Figure 2 (41 students). For these two laboratory sections, the target concentrations were 1.50×10^{-4} M (± 0.05) and 1.83×10^{-4} M (± 0.06), respectively. All data lying outside of the dashed-lined box in Figures 1 and 2 are unacceptable. Typical propagation of uncertainty calculations for this procedure range around ± 0.03 molar units, if perfect laboratory technique was used. Thus, we allowed for some additional laboratory error by the student and doubled the propagation of uncertainty error value to 0.06 M.

The results shown in Figures 1 and 2 are surprising and disturbing. By this point in their academic careers students are expected to have learned how to make basic solutions and conduct dilutions. A typical response from faculty members that we have discussed our results with is that there must be a flaw in our educational approach. But note, for these very same students, 79% of them scored higher than the average

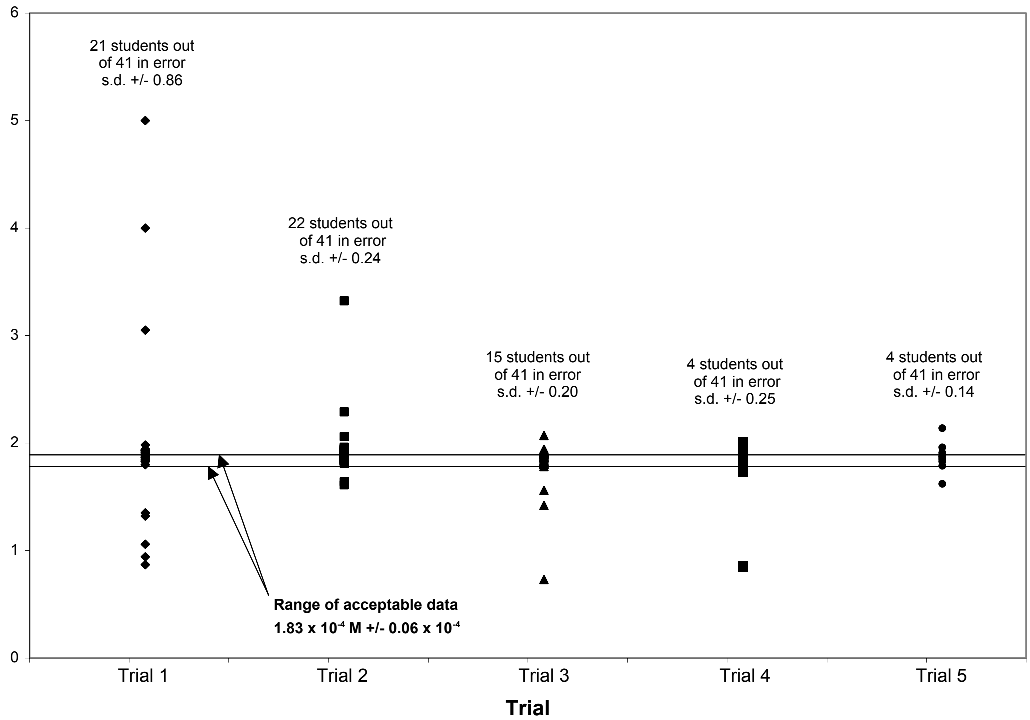

Figure 2. Summary of results for 41 students asked to make a 1.83×10^{-4} M solution of Ca^{2+}.

Table 3. Summary of Dilutions Used to make a Solution. Data were Taken from Two Sections of Laboratory (41 Students Total)

Mass of $CaCO_3$ weighed out (g)	Mass of $CaCO_3$ placed in X volumetric flask (mL)	Subsequent dilution (mL pipet to mL volumetric flask)	Resultant conc. (M Ca^{2+})	Number of Students using this Approach
0.114	250	10/250	1.83×10^{-4}	1
0.183	100	1/100	1.83×10^{-4}	19
0.183	250	5/500	1.83×10^{-4}	1
0.183	500	5/100	1.83×10^{-4}	7
0.229	250	5/250	1.83×10^{-4}	1
0.457	250	25/250 twice	1.83×10^{-4}	2
0.456	250	1/100	1.83×10^{-4}	4
0.457	250	5/500	1.83×10^{-4}	2
0.458	500	5/250	1.83×10^{-4}	1
0.458	500	2/100	1.83×10^{-4}	1
0.916	500	5/500	1.83×10^{-4}	1
0.916	500	10/100 twice	1.83×10^{-4}	1

reported score for the 1998 standardized ACS general chemistry examination given at the end of the year. These students have completed laboratory exercises similar to those at other colleges and they are not lacking in a theoretical understanding of chemistry. Their inability to complete this exercise may also explain errors in their other laboratory experiments (titrations and analysis of unknown samples) and may be the answer to the common question "What did I do wrong, I followed the procedure?" The typical answer to this question is it must be their technique, yet we never directly test individual steps in a laboratory procedure. Figures 1 and 2, as well as data in Table 1, show that the students' ability to make the solutions improved as they made additional attempts.

If we also look at how the students performed as the week of laboratory sessions progressed, we find an interesting improvement. Data in Table 2, indicate that the students preformed better later in the week. There are two possible reasons this trend. One of these is the modification of the prelaboratory presentation. On Monday, we gave very little prelaboratory instruction because the students have made solutions and preformed dilutions in the past; we expected this to be a straightforward exercise. As a result, we saw a high level of difficulty in completing the proper calculations and in making the solutions. For the laboratories on Tuesday and Wednesday, we reviewed details on how to properly make solutions in the prelaboratory lecture (details that the students should have remembered from earlier in the semester). This resulted in a 10 to 15% improvement in student performance. On Thursday, we added additional details on weighing and demonstrated two dilution techniques as they would be performed in this laboratory. The students from Thursday had reduced their first-try errors to 21%. The important point of this evolution of the prelaboratory demonstration is that we (and most other chemistry professors) originally assumed that the student knew this material because it had been stressed in previous laboratory exercises, but as demonstrated by the students this critical information had not been retained. This stresses a deficiency on our understanding of what our students view as important and what they retain.

The other possible explanation of increased student performance on Thursday is student–student interactions. By the end of the week, students who completed the exercise earlier in the week could have discussed the laboratory with students from Thursday, although we asked them to not do so. We did collect all laboratory sheets and changed the target concentration each day. The fact that we needed to give detailed instructions and demonstrations on how to make the dilutions also justifies that such an exercise be conducted in general chemistry laboratories—if for no other reason than to re-iterate how to properly perform these tasks.

It is interesting to describe how the students approached the calculation portion of the exercise. Thirteen students had difficulty with the calculation portion of the exercise and needed extra hints to complete the exercise. Approximately 4% of the students started by randomly selecting a weight of $CaCO_3$ and tried to combine pipet and volumetric volumes to reach the specified concentration. Obviously, students using this approach did not succeed. Most students (96%) immediately noted that they could weigh out sufficient $CaCO_3$ to make a 100-fold concentrated solution, and then dilute it 100-fold to reach the desired concentration; however, several different combinations of pipets and volumetric flasks were used to reach this 100-fold dilution. Results in Table 3 (for two laboratory sessions that made the same concentration) show that the most common strategy for making the solution was to weigh out 0.183g of $CaCO_3$, dissolve it in 100-mL of deionized water containing 1% nitric acid, and make a 1-mL to 100-mL dilution, but other weights and dilutions were also common. Of the 126 students completing this laboratory exercise, only one student remembered to correct for the purity of $CaCO_3$ (99.4%). More students would possibly have made this correction if the $CaCO_3$ not been essentially pure. Results in Table 3, also show that many students were not conscious of the waste generated by using 250- and 500-mL volumetric flasks. This point was not stressed in the prelaboratory lecture but may be noted in the future.

Student Evaluations

Most of the students did not like this laboratory exercise during its performance and strongly expressed their opinion. This is surprising because students usually like direct-grading techniques and nothing is more direct than taking away five points for each mistake. Five students became so frustrated that they left the laboratory prior to finishing it; however, chemistry exercises should not be based on popularity, especially when it comes to important tasks such as the making of a solution. During subsequent laboratories students did note that they were more confident with the laboratory techniques when making dilutions. We plan to continue the use of this laboratory at the beginning of the second semester until we ensure ourselves that students are capable of making solutions given the training obtained in first semester.

The results of our pedagogical experiment will come as no surprise to experienced laboratory instructors because this topic—the lack of student ability to perform dilutions and properly make solutions—has been the point of many hallway conversations at ACS meetings. The data provided herein can serve as a starting point for future educational efforts. We hope that this article will stimulate more discussion of this problem and provide a direct means of testing the ability of your students. We encourage you to evaluate your students and are interested in your results.

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Supporting Materials. A supporting file is available containing; Solutions, Weights and Lab Technique, Solutions Data Sheet, and Instructor Notes (http://dx.doi.org/10.1007/s00897020581b).

References and Notes

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