Teaching Failure in the Laboratory

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Turning Mistakes into Learning Opportunities

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Many undergraduate science students are misled by "cookbook" laboratory experiments that make science appear to be easy and to always yield anticipated results. This is a direct consequence of the pedagogical approach normally used in science teaching—we use experiments that are "guaranteed" to work. This robs the educator of the valuable lessons to be learned from failure. This article outlines one experiment that uses failure to teach a better perspective on the reality of scientific inquiry.

Student success has always been the focus of education. This vision was described by the NSF, which declared that "All students [should] have access to supportive, excellent undergraduate education in science, mathematics, engineering and technology, and all students [should] learn these subjects by direct experience with the methods and processes of inquiry" (NSF 1996, 96).

Requisite to this report is the idea that science programs must encourage and nurture students in subjects that seem forbidding and remote, if not impossible, and that have traditionally been viewed as the proper domain of only the few. The federal government has also adopted this pedagogical approach in its "leave no child behind" educational policy (U.S. DOE 2001). These documents outline strategies to educate students in the physical sciences. An emphasis is placed on disseminating teaching techniques and laboratory experiments that are "known to work." In other words, we, as educators, are expected to use clear and concise examples in our teaching and in the laboratory, where student success is guaranteed.

Although we agree with the spirit of these initiatives, we find fault with what is a glaring omission—namely, the fact of failure in science is not addressed. As educators, we use examples or laboratories that demonstrate particular concepts. Pedagogically, we want to use tools that will work. In the chemistry laboratory, that means using experiments that are foolproof, essentially turning this supposed discovery process into a lesson in cookbook chemistry.

Although foolproof experiments are educationally sound (they do illustrate points after all), they do not prepare students interested in the sciences for the reality of scientific inquiry; things do not always work as expected. We believe that many instructors are missing excellent opportunities to teach students how to cope with failure and how to learn from it. Therefore, we believe in incorporating the reality of scientific inquiry (i.e., failure) into the undergraduate science curriculum.

Designed to Fail

The genesis for the idea of teaching failure in the laboratory arose from a series of experiments carried out by upper-level chemistry majors in an Organic Preparations laboratory. This course is designed to expose these students to advanced laboratory techniques that are not normally introduced in the regular organic chemistry sequence.

To create a foolproof laboratory to illustrate to undergraduate students the chemistry of amines, we asked graduate students in the Organic

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Preparations lab to survey the chemical literature for methods to reduce aromatic nitro compounds to the corresponding amines. The specific reaction is outlined at the top of Table 1. The graduate students found a large number of preparations for this type of transformation, and each tried a different one. We, of course, screened these methods to assure that each was safe for undergraduates to perform. At the end of the experiment, the class compared the results of their efforts (see Table 1).

Of the 10 methods tried, only one (entry 6) met the criteria of a laboratory adaptable for the undergraduate cohort. The reaction can be completed in one laboratory period, is easy to perform, gives a respectable yield, uses reagents and methods that are extremely safe for novice scientists, and does not incur any extraordinary waste disposal requirements. Although other methods worked well (entries 2, 3, and 4), these reactions either required apparatus not normally found in an undergraduate teaching laboratory or were too difficult to complete in one laboratory period.

We were satisfied that the class had achieved our major objective. We now had a laboratory illustrating the chemistry of amines that could be easily incorporated into the sophomore-level organic chemistry curriculum.

Unanticipated Results

As it turned out, we achieved more than our initial objectives. During our discussion of the various methods used, students voiced disbelief that methods taken from the literature did not always work. We were surprised by their reaction to something we take for granted—reactions often fail. This led to an excited discussion about the realities of chemical research:

- There are usually many ways to effect a particular chemical transformation.
- Which method is chosen depends on the nature of the compound at hand.
- A trial-and-error process is used to choose the most appropriate method for a particular circumstance.

We explain to our students that scientists try the "standard" methods first, and, if those fail, try more esoteric methods until one works. When choosing a method, one has to consider all possible chemical incompatibilities and avoid those methods that may result in an unsatisfactory outcome (as for entry 1 in the table below). Also, as chemists, we must recognize that many great advances are made from "failed" outcomes. It is from the exploration of failure that many valuable chemical insights are gained.

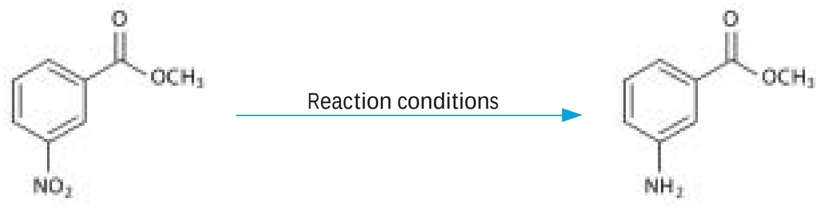
Students commented that they had never been exposed to this before. In fact, they were under the impression that all chemical reactions work as advertised, because that is the experience they have had in all of their undergraduate laboratories. This is a dangerous precedent to set for novice scientists, and is the direct result of our pedagogical approach to teaching science.

To illustrate the value of this new approach to teaching failure, we have collected several student comments below (we have added parenthetical narrative for clarity when necessary):

- It was interesting to see that even the method for reducing this compound that was taught in class ($SnCl_2$/HCl, entry 7 in the table) failed. That was strange. But, our class discussion with Dr. G

TABLE 1

Results for the reduction of an aromatic nitro compound to the corresponding amine.



Entry	Reaction conditions	% yield	Comments
1	Zn, NaOH (Martin 1943)	0	Ester hydrolysis product isolated.
2	H_2, 5% Pd-C (Mendenhall and Smith 1973)	82	Requires hydrogenation apparatus.
3	Sn, HCl (Clarke and Hartman 1941)	73	Reaction time is 4 hours.
4	Fe, HCl (Fox and Threlfall1973)	70	Column chromatography necessary for purification.
5	Zn, $CaCl_2$ (Kuhn 1943)	0	Starting material isolated.
6	Pd-C, H_2NNH_2 (Bavin 1973)	89	Two hour reaction time and complete reduction effected.
7	$SnCl_2$, HCl (Woodward 1955)	0	Starting material isolated.
8	$FeSO_4$, NH_4OH (Smith and Opie 1955)	0	Starting material isolated.
9	$NaBH_4$, $Cu(AcAc)_2$ (Hanaya et al. 1979)	0	Starting material isolated.
10	$Na_2S_2O_4$, NH_4OH (Redemann and Redemann 1955)	0	Starting material isolated.

showed me how that method would work for other molecules but not this one.

- At first I didn't get the point. Why try things that won't work? Now I know that getting a chemical to react can be more complicated than I had been led to believe.
- This was really cool! We didn't know which way would work, and it really showed me that sometimes when things go wrong, it's not always my fault.
- This felt like real science. Everybody tried really hard to make their reaction work. I was surprised that I did something completely different to the molecule than what was supposed to happen (Zn/NaOH, entry 1 in the table). Our class discussion showed me that these conditions are not compatible with this compound.

There were many comments in the same vein indicating that this was a new and valuable experience for students. More than 90 percent of the class rated this experiment highly in terms of the effectiveness with which it demonstrated the difficulty of scientific inquiry and the eventuality of failure in science.

Other comments were not as laudatory. Several students indicated that we had simply proven that a difficult topic like chemistry was even more difficult than they had imagined. It seems the point was lost on this minority. However, this is to be expected from almost any student population. In the future, we will spend more time in the pre-lab explaining the learning outcomes expected from the exercise. Perhaps, in this context, more students will appreciate the experiment for what it is—an experiment.

Conclusions

What started out as an exercise in finding a "foolproof" experiment to incorporate into the undergraduate laboratory curriculum became an opportunity to teach the eventuality of failure in scientific work to both undergraduate and graduate students. Both groups learned how to overcome and learn from that failure. This has led us to use this experiment in the undergraduate chemistry curriculum. Students perform reactions that we know will fail, and then, as a class, discuss possible reasons for these failures and what insight we can gain from this exercise. We hope that using failure will add a new dimension to the process of science education and will better prepare future scientists for the failures they will undoubtedly encounter in their careers.

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