provocative opinion

A Physical Chemist Looks at Organic Chemistry Lab

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It must be almost unique for a physical chemist to stray into organic chemistry in midlife, and so this paper is perhaps most like an anthropological report about this strange country and some of its even stranger inhabitants. My mission was not to learn to be an organic chemist, but to learn to teach the lab component of it, and to learn to design synthetic experiments at the microscale.

So in 1985 I spent the summer at Bowdoin College working with Dana Mayo and Ron Pike, learning organic chemistry by total immersion. I worked in the same lab with five undergraduates (and a black cat named Steroid) who were testing the final versions of the experiments to be included in the Mayo–Pike masterwork. At first I tested experiments so as to master the technique, then I started trying to design my own, first by scaling down preps from the *Journal of Chemical Education*, then by trying to go beyond it to create new puzzles.

The most striking and immediate parallel to my experience is going to a country where you do not know the language and learning it without learning the grammar. I still do not know the grammar of organic chemistry, but I know a lot of words, and further I now perceive regularities that I did not when I first visited that land 20 years ago. When I realized that the Perkin condensation was just a replay of the Grignard reagent attack on carbonyl, then I saw suddenly in a blinding flash that an enormous part of carbonyl chemistry could be explained by looking at negative species attacking the carbon end of carbonyl group, followed by the dehydration of the resulting molecule.

The astonishing thing is that it took 20 years for me to see this. Partly it is that I have learned how to learn science—that one looks for regularities, not isolated facts. But also, organic chemists themselves, threatened with memory overload, have systematized their discipline to a remarkable degree in the past 20 years, so that the essential character of it—a fuguelike repetition and combination of a few essential themes—is much more evident.

But my special interest is the use and abuse of teaching labs, and here there is a sharp divergence between organic chemistry as taught and organic chemistry as practiced. As far as I can tell, no real organic chemist goes into the lab, follows a prep and says "Today we're going to make aspirin and prove that we've got it." He or she says "Suppose I treat X with Y; if the mechanism is thus and so, I should get Z." When Z* appears, the stage of pondering begins, followed by a lot of inscrutable curved arrows. In the end the conclusion is that the mechanism is not thus and so, but something else, which immediately suggests the question, "Now if I treat X* with Y*, will I get Z**?" From countless experiments a sediment of experience is built up. This sediment is eventually metamorphosed into a "mechanism".

Yet organic chemists persist in using teaching lab experiments to "illustrate" a mechanism. Run a dehydration of methlcyclohexanol, they will say, to illustrate carbocations chemistry, an E1 mechanism, or some similar abstraction. What you illustrate in a lab is that one liquid (colorless) is tuned into another (brown) and then after some work into another liquid (colorless). You will never see a single carbocation, or a single hexagonal benzene ring. These ideas are postulated to explain reality, and they are not illustrable in the lab even though they arise logically as a way to explain laboratory data. The lab is not a good way to illustrate abstractions, and now with modern audiovisual aids, it is not needed for this role. With lap dissolve projection, carbocations can hurtle across the room at 10^9 times life size.

It is the *process* of abstraction that is so badly ignored in our labs. Organic labs have degenerated into cooking, and whether you cook at macro- or microscale is a mere detail. The distinction between organic chemical research and cooking is not in the operations, but in that a cook is concerned only with the creation of a product while an organic chemist wants the answer to a question. In science, technique is always subordinate to the goal of putting a question to Nature and getting an unambiguous answer.

I am not against cooking. Some of my best friends . . . . But real organic chemists only cook when they cannot buy it from Aldrich. Organic chemistry is an inquiry into a specific aspect of Nature, not an involved set of finger skills. Who would guess that from our teaching labs? Our labs show what organic chemists do with their fingers, but not what they do with their brains, and no longer represent the field as it is *today*.

In physical chemistry labs there are unknowns. There are numerical facts to be determined. The thought process is like real physical chemistry. Yet only a few organic experiments have any puzzle component at all, and it is the point of this essay to champion this idea. Some examples of simple but quite real puzzles include a recently described experiment (*1*) in which students acetylate an unknown alcohol, then use NMR to figure out which five- or six-carbon alcohol they have. This uses NMR for something other than characterizing a known. Or the recently reported experiment in which an unknown aldehyde is condensed with an unknown ketone to produce one of 25 possible aldols (*2*). Consider the reaction of triphenylmethanol, the product of a classic Grignard reaction, with HI. Who would suspect that it is the H, not the I, that ends up bonded to the central carbon (*3*)?

All these problems, and I can think of many more, are *puzzles*. They require thinking exactly the sort that our premeds will use to solve diagnostic problems. And they are the same sort of thing that real organic chemists spend their time solving.

Now, dear reader, you are going to say, "Pickering, don't you realize that our students have all they can do just to cook? And you want to pound more things into their fur covered brains?"

Johnstone, in an intriguing set of papers, hypothesizes that our labs are difficult because we provide so much information that the student's short-term memory overflows (*4*). Kozma has shown that "high structure" lab materials (read "recipes") are preferred by students and that students get out of lab faster (*5*). And last but not least, I can tell you from personal experience that doing organic is *hard*. The procedure part of lab is quite difficult enough.

But there is a simple compromise. Let the student think about procedure in lab and theory after the lab. The natural time for theoretical ponderings is when the report is being written up. We have got to devise grading systems focussing the student's attention on the puzzle aspect, not just yield and purity. When frying chicken, the object is to produce a given amount (yield) of satisfactory flavor (purity). But organic chemistry is not cooking, although it is graded as though it were. The only people who do not seem to recognize the distinctions between cooking and organic chemistry are those who design our organic teaching labs. Probably the "cook it up and see the pretty color" approach derives from an unconscious urge to convince the student that organic chemistry is a useful discipline—that it can be used to make drugs, dyes, nerve gases, etc.

One could, of course, ask whether or not organic chemistry is not self-evidently useful and, in a large sense, whether things are worth learning because they are useful or because they are interesting. But this takes us far afield.

I have been beating on this need for intellectual content in labs for years (*6*, *7*). In freshman chemistry this plea has been heard. There is a long history of such semidiscovery labs at the University of Michigan (*8*, *9*). Even that bastion of by-the-numbers education, the U.S. military, is experimenting with guided inquiry labs at West Point (*10*).

But the holdouts are organic chemists. This is not just my opinion, it is hallowed by statistical studies (*11*). There is some sort of cosmic futility in most organic labs. Make a white powder, prove that it is what you expect, donate it to chemical waste, again, and again, and again, if not to the last syllable of recorded time, at least until the end of the semester. But why not do something with the white powder? Why not keep the identity of the white powder unknown and then demand that the student choose from a possible menu of products, and then choose from a menu of mechanisms?

There is little doubt that scaling labs down makes sense for a lot of reasons. The microlab offers a real chance to reform, but not only because it is safer and more pleasant but also because it is very much faster (*12*). Thus the number of puzzles/hour can be increased enormously over the cooking labs so prevalent at the macroscale. This is its ultimate pedogogical justification. But if organic lab is to be devoid of thought, it does not matter what the scale is. The creation of white powders for the sake of white powders at any scale reminds one of the character in Camus's *The Plague*, who, in a final symbol of existential futility, moved peas one by one from one pan to another and then back again.

The micro–macro debate has been carried on as though the teaching of technique was what really mattered, in spite of the fact that most of our students profoundly hope never to see the inside of an organic lab again. What matters for them is not practice of the finger skills of organic chemistry, but practice in the style of thinking of organic chemists. The micro lab is a marvelous chance to change this. Bring thought back into the organic lab! Show how startlingly interesting the field really is!

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