Strange Bedfellows: Organic Synthesis and Essay-Writing

Interface

Index Terms*—*Composition, problem solving, science pedagogy, writing in the sciences, writing pedagogy.

—Feature by
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Organic synthesis is the branch of chemistry that deals with the step-by-step conversion of relatively simple starting materials into larger, more complicated, target molecules. Synthesis problems given to undergraduates can often be solved in three or four steps; practicing chemists routinely tackle syntheses that contain 50 or more steps. There are two components to organic synthesis. The first involves the generation of a hypothetical sequence of reactions written on a sheet of paper, as shown, for example, in [Fig. 1]. The second is the process by which these reactions are carried out in the lab.

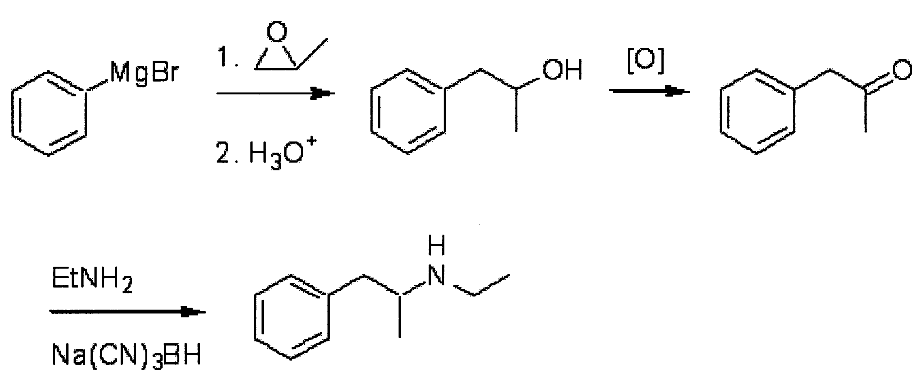
Among practicing chemists, these components are tightly linked; results obtained in the lab lead to modifications of the hypothetical sequence, which lead to changes in what is done in the lab, and so on. Interviews with undergraduates and graduate students involved in solving synthesis problems, however, suggest that there is little (if any) connection between the synthetic schemes the students propose on paper and the procedures that would have to be carried out in the lab to effect these transformations.

This paper will focus on the process by which hypothetical synthetic schemes are generated on paper. As part of a long-term effort to understand how students and early-career practicing chemists learn organic chemistry, we have obtained results that have lead us to propose an analogy between the process by which essays are written and the process by which organic synthesis problems are solved.

In the process of writing an essay, the author uses knowledge of vocabulary, syntax, and discourse to creatively organize and then produce a paper. In the process of generating a synthesis, the chemist uses knowledge of structure, functional group reactivity, and reaction mechanisms to creatively organize and then produce a synthesis.

Both the writing of an essay and the design of an organic synthesis are goal-oriented, nonlinear, recursive activities that lead to a product that is greater than the

Fig. 1. Three-step synthesis of Apetinil, an appetite suppressant, from common starting materials.



sum of the individual elements involved in its creation. For novices, both activities can be difficult because they require individuals to actively pool all the aforementioned elements to develop their own solutions. Novice writers often focus on individual sentences and have difficulty linking these sentences together into a coherent essay. Novice chemists tend to focus on the details of individual reactions, have difficulty connecting these reactions into a rational synthesis, and get lost in the details. Essay writing and organic synthesis share another common attribute: It is much easier to follow someone else's essay or synthesis than it is to produce an essay or synthesis of equivalent quality by oneself.

Although the products of essay writing and the creation of a synthetic path appear to be as different as possible, we have discovered similarities in the process by which these products are generated. Furthermore, the literature on composition has helped us understand some of the difficulties students face in learning organic synthesis. This paper will examine the differences between novices and practitioners in each field by demonstrating the connections between these seemingly disparate pursuits.

One of our goals is to probe the extent to which gaps in the research literature in one of these fields might be filled by results from the other. We will draw on results from the two studies that we have done. One involved undergraduates who were finishing up the year-long course in organic chemistry taken by sophomore chemistry and chemical engineering majors. The other studied the problem-solving behavior of first-year graduate students enrolled in a graduate-level course in organic synthesis.

SOCIAL ACTIVITY

One of the most significant differences between novices and practitioners involved in both essay writing and organic synthesis is the environment in which these activities occur. For practitioners, there is a social element to these tasks. In both fields, practitioners spend time discussing their work with peers in the form of "shop talk." Novices, however, rarely engage in equivalent interactions. Hounsell noted that "the students say either that they do not discuss their essays with one another or that, if they do, discussion is never about content or how one might approach a particular essay . . ." [1]. This discrepancy was reflected in conversations among students, as captured in the following quote:

> Graham: *They* [the students] *talk to each other about how they haven't finished it on time, and, oh, 'I have to get an extension', and this kind of thing. But they don't really discuss essays.*

Hounsell concludes: "[e]ssay-writing seems therefore an essentially private activity [for the students]." The same phenomenon was observed in our work with students of organic synthesis.

Professional writers strive to connect with an audience, while practicing synthetic chemists propose syntheses with the aim of making them viable in the laboratory. Writers, therefore, keep their audience in mind as they prepare their final drafts, while synthetic organic chemists spend an inordinate amount of time predicting the feasibility of their proposals. Hence, practitioners in both fields are constrained by the environment in which they work to create a product that is "viable" in a world without a grading scale. Thus, they generate products that are more likely to be accepted by a society of peers or consumers.

Students, however, treat both composition and synthesis as private activities because they view them as classroom-based exercises. When writing, they seldom worry about whether their essays connect with an audience. When proposing a synthesis we've found that they seldom consider whether the route they are proposing has the slightest possibility of being realized in the lab. Their only goals are those associated with performance in their classes. In their study of problem solving in organic synthesis among first-year graduate students, Bowen and Bodner [2] noted that the participants rarely, if ever, worried about the viability of their synthesis from the perspective of what occurs in the laboratory.

By not considering the reality of what "works" in the laboratory, the participants in this study lost one of the most important evaluative tools employed by practicing organic chemists. Consider, for example, the reactions in Fig. 2. The first reaction, between an electron-rich diene and an electron-poor dienophile, is "doable;" it would work in the lab. The second reaction looks good on paper and can be found in many introductory textbooks, but it would only work under conditions of extremely high temperature and pressure and, therefore, is not "doable" in the real world of the organic synthesis laboratory.

The social nature of both synthesis and composition affects the quality of the final product in another way. Harris notes, "We write not as isolated individuals but as members of communities whose beliefs, concerns, and practices both instigate and constrain, at least in part, the sorts of things we can say. Our aims and intentions in writing are, thus, not merely personal, idiosyncratic, but reflective of the communities to which we belong" [3].

We believe that realizing these constraints helps practitioners refrain from the nonsensical responses often obtained from students on exams or other work submitted for grading. Because much of the content of this work has no higher order meaning, students don't feel any particular restraint in submitting work that is often unlikely to the point of absurdity. A common occurrence among our undergraduates, for example, was the invocation of a "magic reaction" that would carry out an impossible transformation.

In addition to differences in the overall quality of the final product, differences in meaning result in differences between the way students and practitioners approach their tasks. Novice writers frequently use what is called an egocentric approach [4], or what Flower calls writer-based prose [5], in which the writer not only neglects the audience but forces his or her approach upon a topic and argument.

We observed a similar approach by graduate students enrolled in the synthetic organic class. Students often got fixated on a reaction or a strategy that they wanted to impose on their molecule rather than exploit the reactive propensities of the molecule. By forcing such tactics, our participants were doomed to a less-than-optimal final solution.

The social nature of synthesis and composition among practitioners of these fields suggests that meaning-making dictates the elegance of the final product. Not only do we believe meaning to be the underlying factor that distinguishes practitioners from students in both disciplines, but we also feel that the gap in meaning-making is most prominently manifested in the planning and editing stages.

PLANNING

Comparisons between our work and the literature on composition suggest one of the major similarities between these apparently disparate fields is the role of planning in both pursuits. The primary tool practicing synthetic chemists use to plan a synthesis is known as retrosynthetic analysis. Retrosynthesis depends on the perception of structural features in the products of the reaction that are manipulated in a reverse synthetic sense to deduce the optimum starting materials for the reaction [6].

Retrosynthetic analysis simplifies the problem at hand. When working backward from the target molecule, there are only a few possibilities for each step. When analyzing the problem in a forward-based strategy, the entire battery of organic reactions could potentially play a role at any given point in the synthesis. Retrosynthesis also gives a clearer starting point for attacking a problem, which is a major stumbling block for novice problem solvers. Fig. 3, for example, illustrates a retrosynthetic analysis of how the target molecule on the left can be made from the starting material on the right in a two-step reaction. Fig. 4, on the other hand, shows a less efficient synthesis of the same target molecule from the same starting material that was generated by one of our undergraduates on the basis of working forward from the starting material.

Flower and Hayes made similar observations in the realm of composition. In their cognitive process model they argued that "writing is best described as the act of juggling a number of simultaneous constraints" [7]. They concluded that planning is

Fig. 2. Viable Diels-Alder reaction compared with a Diels-Alder reaction that would be difficult, if not impossible, to carry out in the traditional organic lab.

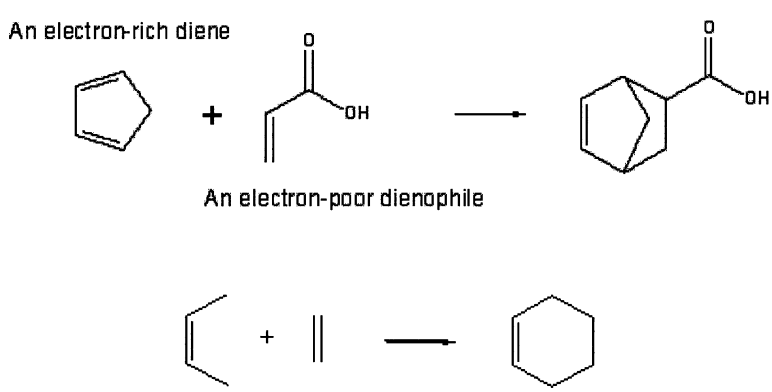
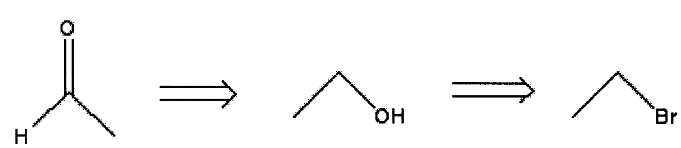


Fig. 3. Simple retrosynthetic analysis of how the product shown on the left could be synthesized via the intermediate in the middle from the starting material on the right.



the key to reducing the cognitive load exerted by those constraints, just as retrosynthetic analysis reduces the complexity of a synthetic problem.

Specific methods for reducing the cognitive load that Flower and Hayes suggested were partitioning the problem, setting priorities, and choosing to "satisfice." Interestingly, each of these strategies has a counterpart in the realm of synthesis. Flower and Hayes suggested, for example, that the goal of partitioning a larger problem into smaller ones is to produce more manageable tasks [7]. Synthetic organic chemists routinely engage in convergent synthesis in which a target molecule is broken down into smaller fragments. Not only does this strategy produce a better overall laboratory yield of the product, but it also reduces the complexity of the problem in hand.

"In setting certain priorities, writers in effect eliminate some other constraints or reduce the level at which they will be deemed satisfied" [7]. Similarly, synthetic chemists will generally determine their priorities, including showcasing a particular method, before embarking on their retrosynthetic analysis. Lastly, Flower and Hayes stated that "[a] writer 'satisfices' by choosing to take the first acceptable solution" [7]. This technique allows the writer to seamlessly move on to another part of the problem without losing the train of thought, while having the flexibility of polishing at a later time.

Eventually, the more menial tasks become a part of subconscious routines. "[E]xperienced writers usually devote very little conscious attention to tasks such as typing, producing grammatical sentences, or even meeting the demands of a particular genre, whereas these tasks can overwhelm inexperienced writers" [7].

In proposing a new model of writing processes, McCutcheon similarly observed that novice writers are hampered because too much of their working memory is occupied by low-level skills such as text generation [8]. We saw an analogous behavior in our research on organic synthesis. Practitioners pay less attention to the specific reagents they use when proposing syntheses and, consequently, give more attention to the overall goal.

Just as the notion of planning is important for both pursuits, there are also similarities in how that planning is actually carried out. Practitioners in both fields do most of their planning on paper. In our research on synthesis by undergraduates, we found that students do very little planning on paper. Pianko also noted a similar trend in her work with students in a freshman composition course [9]. In her study, the vast majority of the participants did their planning mentally, rather than on paper, even though most of their pauses were for planning ahead. Pianko argued that these pauses were often detrimental because they contributed to the participants losing their trains of thought.

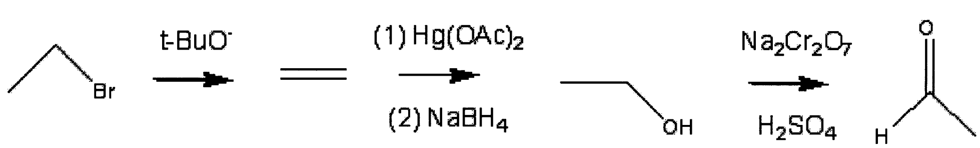
We believe that this reluctance to plan on paper makes the students' tasks more difficult due to the cognitive overload described by Flower and Hayes [7]. More recently, Flower showed that experts' plans were far more elaborate than those of novices [10]. She found that not only were the experts' plans more integrated at the top, they were also flexible, so that they could even be radically adjusted as needed.

Writing out thoughts on paper can help reduce the cognitive overload that occurs when one tries to keep all the information relevant to the task in one's head. Another advantage of committing our thoughts to paper is that it frequently changes our representation of the problem. Flower and Hayes note that "one of the most telling differences between our good and poor writers was the degree to which they created a unique, fully developed representation of this unique rhetorical problem" [11].

Approaches to planning are also affected by the conception of the task. In his study of college students, Hounsell concluded, "the main findings of the study pointed to the necessity of an understanding of planning strategies in relation to students' conceptions of essay-writing" [12]. Therefore, writers plan according to the goals they want to achieve. In organic synthesis, the aim of the synthesis dictates the nature of the plan. In target-oriented synthesis, for example, where the aim is to produce a specific target molecule, the aim of the plan is to produce the most efficient route to the specified product. However, in diversity-oriented synthesis, where the purpose is to produce a variety of products of similar structure, the goal is to come up with a plan that is flexible rather than just efficient.

A corollary to this discussion of planning is that students spend relatively little time in the planning stages for either essay writing or organic synthesis. Hounsell suggested that "organizational aspects of learning cannot be considered in isolation from referential meaning"

Fig. 4. Less efficient synthesis proposed an undergraduate on the basis of working forward from the starting material.



[12]. He argued that students spend less time on planning because they do not understand how it can help them.

We have observed the analogous situation in our synthesis work. We found that students paid little, if any, attention to planning, either because they did not see the value of retrosynthetic analysis. When they used it, they often did so for authoritative reasons—their instructor told them that organic chemists use retrosynthesis when planning a synthesis—or because they were stuck and had no choice. They were not convinced of its utility, however, because they didn't understand how retrosynthetic analysis could simplify the problem-solving process, and it is unreasonable to expect students to be highly vested in a technique they do not really trust.

In their study of the use of outlining by undergraduate students, Walvoord et al., found analogous situations. They noted that most students outlined after a period of free writing. Furthermore, "[s]ome students treated each generic heading of the outline merely as a box into which to dump, in any order, material that pertained to that heading" [13]. This tactic is similar to performing only a single round of retrosynthetic analysis and then switching to a forward-based strategy.

EDITING

In their studies of the process of composition, both Perl [4] and Pianko [9] observed that "[e]diting is primarily an exercise in error-hunting" [4]. Neither researcher saw the students engage in any substantial revisions. Our graduate students tended to focus on a single synthetic route and never considered changing to another plan, even when it became clear to them that their current plan had become so inefficient they would lose significant credit on their overall grade for the project.

Neither the graduate nor undergraduate students seemed aware that they should perform any evaluation of their proposed synthesis, and expressed surprise when asked: How would you judge the merit of your work? Similarly, Wallace and Hayes [14] noticed that students seemed unaware that revision could involve anything more than "error-hunting." Their study, however, demonstrated the promise of explicit instruction in that area.

Perl went on to note, "the simple set of editing rules at their disposal was often inappropriate for the types of complicated structures they produced. As a result, they misapplied what they knew and either corrected a hypercorrection or impaired the meaning they had originally intended to clarify" [4]. This misapplication of the rules of editing, or the reactions in the case of organic synthesis, is a major problem with the students' solutions. Because they don't think about the process, or mechanism, of how organic reactions occur, students frequently choose substrates that are inert to their chosen reaction conditions.

Perl also noted that "the students were so certain of the words they wanted to have on the page that they 'read in' these words even when they were absent" [4]. The consequence of this "reading in" phenomenon in organic synthesis is that many molecules would never survive the reaction conditions invoked by the students. The cause for this frequent miscue is that students learn organic reactions using fairly simple compounds, yet they have to evaluate the probability of each reaction in the more complicated context of a large organic molecule. Although they should pay attention to the entire molecule, students only look at the part of the molecule they want to react, thereby ignoring possible side reactions. Consequently, many of their proposals would never produce the target molecule.

CONCLUSION

The overarching aspect to remember is that "[c]omposing always involves some measure of both construction and discovery" [4]. Proposing organic syntheses definitely falls into a similar category. There is an intrinsic difficulty for students in both disciplines: Students have to develop their own solutions because simple mimicry does not get them very far.

The citations in this article clearly illustrate that far more research has been done in composition than in organic synthesis. Perhaps the greatest lesson we can take from the world of composition lies in the following quote, "[t]he conceptions which have been identified are of essay-writing as an activity embracing more than a single essay task" [1]. Typical graduate-level synthetic classes focus on the students' ability to complete one major synthetic project. It seems, however, that having several smaller assignments, with feedback from the instructors, might prove more fruitful for the students. Furthermore, having the students present their work to their peers several times during the term might foster the development of the social environment enjoyed by practicing organic chemists.

The lesson we might offer professional communicators and teachers is evidence for the power of retrosynthetic analysis in the hands of an expert organic chemist. The equivalent form of working backward for writers might involve starting with an explicit statement of the "take-home" message the author hopes the reader would derive from the paper or essay. By working backward, the author can then decide how and where to place the points that support that conclusion.

Organic synthesis can also provide a metaphor for thinking about the consequences of making changes in one part of the "structure," without contemplating the effect these changes have on the whole. Changes in the structure of one of the starting materials in an organic synthesis that seem small can cause serious problems in the final assembly of the target molecule. In much the same way, seemingly small editorial changes in one paragraph can result in logical errors in the structure of the argument being made.

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