What can we do about 'Parker'? A case study of a good student who didn't 'get' organic chemistry

Trisha L. Anderson and George M. Bodner*

Received 1st November 2007, Accepted 8th March 2008
DOI: 10.1039/b806223b

This paper is based on a qualitative study of seven students enrolled in a two-semester organic chemistry course for chemistry and chemical engineering majors that focused on the reasoning the students had used to answer questions on the course exams. Narrative analysis was applied to create case records for each participant that were then subjected to a cross-case analysis of similarities and differences among the participants. The data were found to be consistent with a theoretical framework that differentiates between instrumental and relational learning. The intense speed with which material was covered and the complexity of the material was found to drive even those students who valued a relational understanding towards functioning as instrumental learners. Particular attention is paid to one participant in the study, Parker, who had been a successful chemistry major until he entered the second year organic course.

Keywords: organic chemistry, reaction mechanisms, knowledge transfer, qualitative research, narrative analysis, student-centered research

Introduction

Twenty years ago, one of the authors began a paper on the constructivist theory of knowledge by noting that *"... all too many of us who teach for a living have uncovered evidence for the following hypothesis: teaching and learning are not synonymous; we can teach, and teach well, without having the students learn"* (Bodner, 1986). In much the same way that teaching and learning can be differentiated, there is a significant difference between the relative abundance of chemical education literature that describes recommendations for the teaching of organic chemistry, and the literature that reports studies of the way students learn this subject.

Ideas abound as to what kinds of approaches to teaching might help students learn organic chemistry. Articles can be found advocating approaches such as Peer-Led Team Learning (PLTL) (Gosser and Roth, 1998; Kampmeier *et al.*, 2001; Tien *et al.*, 2002), guided inquiry or discovery learning (Meany *et al.*, 2001; Straumanis, 2004; Gaddis and Schoffstaff, 2007), learning cycles (Libby, 1995), cooperative learning (Dougherty, 1997; Hass, 2000), and active learning in large lectures (Paulson, 1999; Bradley *et al*;., 2002; Carpenter and McMillan, 2003). Other teaching strategies include web-based homework (Katz, 1996), study sheets to aid in understanding voluminous textbooks (Chenier and Jenson, 1983), incorporation of learning communities into the organic chemistry course (Schearer, 1988), and so on.

While we acknowledge the potential benefit of many of these teaching strategies, it should be noted that only a small fraction of the literature on the teaching and learning of organic chemistry has focused on the learning experience from the students' standpoint. Because we believe that student-centered research is necessary if we want to improve the learning experience for students, our group has pursued student-centered research in organic chemistry at both the graduate (Bhattacharyya and Bodner, 2005) and undergraduate (Bhattacharyya *et al.*, 2004; Ferguson and Bodner, 2008a; 2008b) level.

Department of Chemistry, Purdue University, West Lafayette, IN 47906, USA. E-mail: gmbodner@purdue.edu

This paper focuses particular attention on a case study of a student who was given the pseudonym 'Parker'. Parker's case study was extracted from an extended study of second year chemistry majors because discussions with our colleagues who teach organic chemistry have led us to believe he is far from unique; that, for better or worse, there are a lot more 'Parkers' out there.

Parker was a bright, dedicated second year chemistry major who had been a successful general chemistry student the previous year. (According to his teaching assistant, he was one of the top students in a general chemistry class for chemistry majors.) When he entered the two-semester organic chemistry course for chemistry majors, however, he began to struggle. Although he had an excellent understanding of general chemistry topics, he never felt comfortable with his understanding of organic chemistry, and he earned a low grade in the first semester of this class. His experience in organic chemistry, along with other factors, eventually led him to change his major.

The case study that Parker represents struck a responsive chord for the first author because she fell in love with organic chemistry from her first exposure to the field. It struck a responsive chord for the second author because it reminded him of his own experiences more than forty years ago, when he went from being an 'A' student with one of the top grades in the honors general chemistry course to a 'C' student who remained a chemistry major in spite of his inability to find a pattern in the organic chemistry course he encountered in his second year. This paper examines the difficulties Parker faced and tries to elucidate some of the reasons that organic chemistry often proves to be a significant obstacle for chemistry students. Although the methodology applied to the study could only identify the problems that Parker and other students faced, rather than attempt to 'fix' them, we will discuss potential solutions to these difficulties in this paper.

Methods

This paper is taken from a study of students' experiences in learning organic chemistry that focused on the following guiding research questions:

- What strategies do students use to learn chemical reactions in their first organic chemistry courses?
- What factors influence students' adoption or development of particular strategies?
- What impact do these strategies have on students' conceptual understanding of organic chemistry reactions?

The seven participants in this study were volunteers obtained from a pool of students enrolled in a two-semester undergraduate-level organic chemistry course for chemistry and chemical engineering majors at Purdue University. The courses had three fifty-minute lecture periods each week. No recitation or discussion sessions were associated with the course. Each student in this study was concurrently enrolled in an organic chemistry laboratory course during both semesters of the study. The students used Loudon's *Organic Chemistry* textbook (Loudon, 2002). Most of the students also purchased a copy of a detailed set of lecture notes that the professor had prepared for use in the class.

Each student participated in between two and four interviews over the course of the two-semester organic chemistry course sequence. The interviews were approximately one to one-and-one-half hours in length. The interviews were audio-taped and transcribed verbatim. During the analysis of the more than 30 hours of interviews, students were assigned pseudonyms by which they will be referred to in the discussion of the results of this study.

The first interview for the seven participants in the study probed the students' understanding of selected general chemistry concepts, such as reaction rates, equilibrium, and the process of dissolution. The remaining interviews probed the students' understanding of organic chemistry concepts. The framework upon which the interviews about organic chemistry was built was a discussion of the reasoning each participant had used to answer questions that appeared on the course exams that had been taken, graded, and returned to the students prior to the interview. The exams therefore provided a basis for discussing the student's ideas about course concepts, as well as related topics such as their difficulties with the material and their strategies for learning the material. Other questions raised in the interviews were based on observations made by one of the researchers who observed the lectures in this course.

Parker chose not to enroll in the second semester of organic chemistry and therefore participated in only two formal interviews. Informal conversations, however, were held with Parker throughout the first semester that lent us more insight into Parker's experiences, particularly with regard to his decision to change his major from chemistry to another field. They also facilitated comparisons of similarities and differences between Parker and the other seven subjects of the study.

Data analysis

The first stage in the data analysis involved transcribing the interviews verbatim. After the interviews had been transcribed, the transcripts were read and re-read, and important points were highlighted. During a subsequent reading of the interviews, each of the highlighted sections was assigned a preliminary code. The data from each participant was then analyzed individually to form a case record for each participant.

Narrative analysis, a form of narrative inquiry, was used as the guiding framework for this stage of analysis. Narrative inquiry assumes that a given action cannot be understood without knowing the history that led up to that action (Shane and Anderson, 2007). Polkinghorne (1995) argues that 'situated actions' such as these provide a much higher degree of meaning than those same actions in isolation. He illustrates this by noting the following:

> *A story is a special type of discourse production. In a story, events and actions are drawn together into an organized whole by means of a plot. A plot is a type of conceptual scheme by which a contextual meaning of individual events can be displayed. To illustrate the operation of emplotment, I will use a simple story. "The king died; the prince cried." In isolation the two events are simply propositions describing two independent happenings. When composed into a story, a new level of relational significance appears. The relational significance is a display of the meaning-producing operation of the plot. Within a storied production, the prince's crying appears as a response to his father's death. The story provides a context for understanding the crying.* (p. 7)

A key step in the analysis of interview data in this study therefore involved organizing the data from transcripts of the interviews into plots that emerged during the analysis. We chose to use narrative analysis in forming these case records to ensure that each student's story was preserved in order to be told.

A cross-case analysis (Patton, 2002) was then carried out by comparing the case records of the participants in the study, looking for both similarities and differences among the participants. From these comparisons, a series of assertions were generated.

The majority of this paper will deal with Parker's experience in organic chemistry as captured in his narrative, although we will also use the results of the cross-case analysis as we discuss the implications of this work.

Parker's experience

When we first interviewed Parker near the beginning of the organic chemistry course, we found him to be enthusiastic about chemistry and confident in his understanding of the general chemistry concepts discussed in the interviews. We

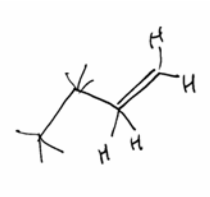

Fig. 1

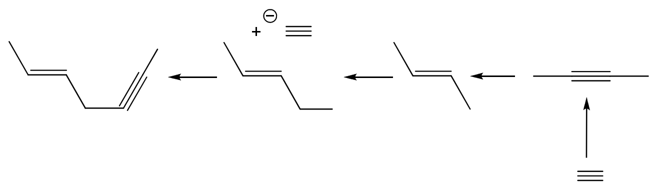

Fig. 2

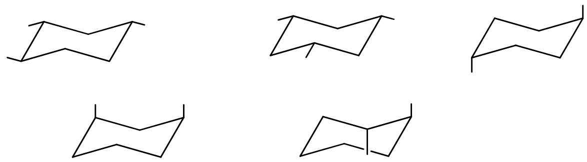

Fig. 3

were therefore prepared to interview this same enthusiastic, knowledgeable student later in the semester. The second interview, however, found Parker dissatisfied with the organic chemistry course and seemingly unable to learn the material that was being presented to him. This stark contrast led us to focus on the following question in our analysis of these two interviews: "*If Parker was so successful in general chemistry, why was he so unsuccessful in organic chemistry?*"

Inability to visualize molecules and reactions

In a previous paper, Bodner and Domin (2000) argued that: *"... students who do poorly in organic chemistry ... tend to handle chemical formulas and equations that involve these formulas in terms of letters and lines and numbers that cannot correctly be called symbols because they do not represent or symbolize anything that has physical reality."* In the analysis of the interviews upon which this study was based, it became evident, once again, that chemical symbols — including Lewis structures, condensed or skeleton structures, and reaction mechanisms — mean very different things to students and practicing organic chemists. It became equally clear that this inability to attribute useful meaning to chemical symbols can present a significant barrier to student learning.

During the second interview, Parker demonstrated a significant level of discomfort with the use of chemical symbols, or 'diagrams' as he called them. He commented, *"Why do you always ... pick the ones [e.g., questions] with diagrams? ... I like the word ones better. I can figure those out."* This discomfort with diagrams was observed in four contexts. Three of these contexts deal with understanding the meaning of the symbols used to represent molecules: (1) deriving the connectivity of atoms from a line structure, (2) translating the two-dimensional structure in an exam question into a three-dimension image, and (3) visualizing the structure and properties of the entire molecule rather than focusing on the individual atoms or elements. The fourth context — the interpretation of chemical reactions as represented by the curved-arrow electron-pushing formalism used by practicing organic chemists — builds on the other three.

Parker's difficulty deriving the connectivity of atoms from a line structure is illustrated in Figure 1, in which he drew a structure with two pentavalent carbon atoms.

Parker was by no means alone in his difficulty interpreting organic symbols. During the second-semester course, the professor discussed the synthetic route shown in Figure 2. After the discussion, a student raised his hand and asked, *"What is the difference between the last two structures?"* on the right in this Figure, not recognizing the difference between 2-butyne and acetylene. This question was so intriguing to the co-author of this paper who was observing this class that she decided to ask the students about it in a subsequent interview. The majority of the students indicated that they had trouble interpreting line structures, not because they were unable to do so, but because it took conscious thought and effort to interpret these structures correctly.

These results are consistent with work done by Calmisiz (2003), who studied the performance of undergraduate chemistry majors on relatively simple organic synthesis problems. He noted that almost every participant in his study transformed line structures with which the problem was presented into condensed structures that indicated the location of hydrogen atoms when solving at least one of the tasks in his study.

Perhaps the best example of the trouble Parker had translating the two-dimensional structures he encountered on an exam into a three-dimensional image can be seen in his answer to an exam question that asked the students to predict which of the conformations shown in Figure 3 had the 'largest total destabilization'.

Parker chose answer 'a' and explained his choice as follows: *"... because the two methyl's were right next to each other, so there'd be the most electron, electron hitting each other. But I don't know if that's true. Cause they're spaced out on all the other ones. I don't know if that's true or not, but that's what I said, and that was my reason why."* It is important to note that the transcript of this interview clearly indicated that Parker's difficulty with the problem was rooted in his inability to form three-dimensional images, not the absence of a conceptual understanding of conformational stability.

Another source of difficulty Parker encountered in organic chemistry resulted from an inability to understand the use of the curved-arrow symbolism that plays such an important role in communicating the mechanism of an organic reaction. Evidence for this can be found in Parker's comment that he began to encounter difficulty understanding the textbook at the point at which mechanistic reasoning became critical. He described the way he studied the textbook in the early weeks of the course as follows:

When I first started reading the book, ... I just had such a good grasp of it through like the first four chapters that I didn't even bother to highlight or anything. ... I just would read ... and I pretty much would grasp it. And I would get to the end, and I'd go back, and I'd look at the study problems, and I'd say OK. So I'd go through and I'd do the homework problems and I wasn't struggling at all.

Parker's difficulties arose when reactions and mechanisms became to take the forefront in the textbook. Although the curved-arrow notation and simple examples were introduced in the first few chapters, reactions and reaction mechanisms became the major theme in chapter five. Parker continued his description of his experience with the textbook as follows:

Then I hit chapter five and it was like hitting a brick wall. And, uh, but I thought I could still get through it the same way, so I tried that and I found it didn't, wasn't working, cause by the time I was at chapter eight I was so lost that I was reading it and I'd go back and read the paragraph I had just read, and I'd be like, I don't completely even remember reading any of this.

Parker indicated that he knew that what he was doing in reading the textbook in these later weeks wasn't working, but he didn't know any strategies for dealing with the material in a useful manner. His trouble with reaction mechanisms did not come from an inability to understand individual reaction mechanisms; it came from a difficulty with understanding the *purpose* of reaction mechanisms. He did not use mechanistic explanations in his responses in the interviews and did not see mechanisms as viable chemical explanations. At one point, he noted:

People didn't sit around with diagrams and figure out, well, this happens like this, you know. You, you came up with reasons why this happens or you'd always, you'd never know what you were going to get. There has to be reasons why, and I feel that his [the professor's] diagrams don't teach that.

Other participants faced similar challenges understanding the purpose of the electron-pushing formalism used to communicate the mechanism of an organic reaction. Consider the work of 'Francine', for example, who drew all of the arrows in a single step in the multi-step mechanism for the reaction in Figure 4, and offered the following insight into her work.

The multiple step thing really kind of throws me 'cause I don't exactly think about it in that. I think of it, OK, I have A plus B, all right, it's going to make C.

As we talked further, it became evident that Francine viewed mechanisms as a way to show where each atom moved in a reaction, as can be seen in Figure 4. She believed that mechanisms were drawn in multiple steps simply to help one keep track of the movement of atoms without getting overwhelmed. This is another example of the difference between the meaning students and practicing organic chemists apply to symbols. To organic chemists—particularly those who teach organic chemistry—curved arrows represent the flow of electrons; to many students they represent the only thing they see in the mechanisms they encounter, the flow of atoms.

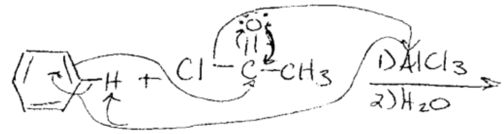

Fig. 4

Tension between learning goals

The lack of a basic understanding of the purpose of organic reaction mechanisms exhibited by Parker and other students in this study provides a basis for discussion of one of the most prominent results of Parker's interviews. One of the reasons he was dissatisfied with his experience learning organic chemistry was a disparity between his goals for learning the material and his perception of the instructor's goals. Parker's primary goal for learning organic chemistry was to understand *why* chemicals behaved the way they did and — regardless of whether it was an accurate view of his instructor's goals for the course — Parker did not perceive this goal to be shared by his instructor.

Parker's perception of his organic chemistry lecture course was captured in his description of his professor's explanation of a particular reaction pathway shown in class: *"Well, if you're wanting to produce this, you know, you just go down this straight line."* He contrasted this approach to the course with what he deemed would be a more valuable approach to organic chemistry, where the *whys* were given greater emphasis.

But why? You know, that's where the real grasp, the real being able to do something with it. It's like, you know, you understand the whys, then you can use it. Then you can really do something with it, and that's what I want to do. I love this stuff cause you could do so much with it, but you can't do anything with it when you don't understand why.

Parker believed that having an understanding of *why* reactions occurred was critical because it gave him the ability to apply what he was learning in new contexts. In a discussion of the β-elimination reaction of an alkyl chloride, he remarked:

That's just a fact. ... That can't be applied outside of this one reagent with that one reactant. And if you gave whys, you could start to predict. You could start to apply it to other things. ... If you know the why for the chlorine, you could then explain and predict this. And at that point, that's when you're grasping. That's when the knowledge becomes powerful, and that's when I feel like I know what I'm doing.

Whereas organic chemists would see this particular β-elimination reaction as a specific example of a generic reaction for which hundreds if not thousands of examples could be found, Parker focused on the specific example presented in class. He noticed a distinct difference between his approach to the course and the way many of his friends approached the course.

You don't understand why, and that's the way it is for a lot of my friends that I talk to. They're like, well, I just *memorized it. I don't know how to explain it to you. And, I want the whys. That's what it comes down to for me, and I think that's what it should come down to, is it should come down to the whys.*

Parker's desire to understand *why* pervaded nearly every aspect of our conversation. From the many available vignettes that could be used to illustrate what Parker wanted to see in his organic course, let's conclude with just one further quote that poignantly demonstrates his attitude toward organic chemistry.

I don't feel like I know what I'm doing because I don't know why. And I think that's what most kids struggle with is that you don't have any why. You don't have any knowledge of what's really going on, so you're just kind of floundering and memorizing. And you get through it and you say, "it's done, it's behind me." *And you don't realize that there's a whole wealth of knowledge that could be tapped into and applied, that's there, but you don't understand the reasons why so you can never apply it.*

The first author attended each of the organic chemistry lectures presented to the students who participated in this study. From her perspective, there was no doubt that the instructor valued having his students' understand *why* organic chemistry reactions occurred. Like most organic chemistry instructors we have observed, he presented these ideas to the students. There was no doubt from the perspective of the authors of this paper that the textbook reinforced the instructors focus on the *why* of organic chemistry reactions. An important question for this study therefore revolved around why Parker couldn't see the explanations of *why* the instructor and/or the textbook presented in spite of everything he did to succeed in a course that he recognized was important for his major. We believe that Parker's inability to view the letters, lines, dots, and arrows with which organic chemists communicate as true symbols contributed greatly to his feeling that organic chemistry was not about *whys*. We are convinced that Parker did not find what he was looking for in either the lecture or the textbook because the *whys* were communicated to the students through structures and mechanisms that utilized lines, letters, curved arrows, etc., that were not symbols for Parker because they did not symbolize anything that corresponded to physical reality for him.

Instrumental learning

Because of his inability to find answers to questions of *why*, Parker resorted to an approach to learning organic chemistry that Skemp (1979) described as *instrumental learning*, which he defined as *"recognizing a task as one of a particular class for which one already knows a rule"* (p. 259), as opposed to *relational learning*, which involves *"relating a task to an appropriate schema"* (p. 259).

An instrumental learner would approach organic chemistry by focusing on the rules for particular reactions, such as the fact that addition of a hydrogen halide to an alkene should proceed in a 'Markovnikov' fashion. Consider Parker's rule-based explanation of an exam question that asked the students to predict which of the compounds shown in Figure 5 would be the major product of the reaction of HBr with 2-methyl-1-butene in peroxide-free media.

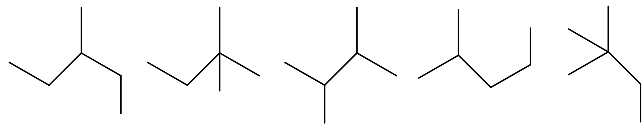

Fig. 5

... I remembered reading a rule someplace [laughs]. That's how good my knowledge of this really is. I remembered reading a rule someplace that they [bromine] go on to the most occupied carbon or something like that — the one with the most bonds.

Further evidence for classifying Parker as an instrumental learner can be found in the approach he took to reading the textbook at this point in the semester, searching for important rules that he then highlighted for ready reference as he solved problems.

When I see something that is important, like a rule or something, I highlight it. And then ... I can hit those points, like, real quick and just like read them. That way, if I'm doing a problem and I'm like, "well, what's the rules?" *I can go back and look at the highlighted sections and then, those are the rules. I don't have to search through everything to try to figure it out, um, what exactly is going on*.

Parker recognized that one of the disadvantages of his instrumental approach to learning organic chemistry was that he found himself encumbered with so many rules that he had difficulty remembering them.

So, the problem I guess I'm having is there are so many rules I'm struggling to associate which rules go with which, cause I'm bad at memorization. I fail anything that had to do with memorization, um, so I really struggle with, oh, this is for boron, but it doesn't work for, you know, aluminum, you know. But, you know, this is for chlorine, but chlorine, but bromine doesn't work this way, it goes this way. And if you put an oxygen [deep breath], and I go whoa!

Another disadvantage of Parker's rule-based, instrumental approach to organic chemistry arose from difficulties he had identifying situations in which he could apply a given rule. As a result, he often applied them inappropriately or in inappropriate contexts. He confused the hydroboration of alkenes with hydrobromination of alkenes, for example, equating boron and bromine.

I try to generalize the rules and the problem is, you can't, because the reason why this is like this is not the same reason why this is like this [referring to two sets of reaction conditions and their products]. So I try to apply generalizing rules like the boron thing to the bromine, but that's not the same. ... But I don't understand the why behind why you can't, so I try to apply the rules in places they can't be applied, and that's what gets me into trouble, I guess.

Parker recognized that his strategy of learning rules was not the best way to learn, but he could find no other approach. "*... my current strategy is just memorize the rules, and that's obviously not working. Because I don't really grasp what's going on, so I need something else. I need a way, I guess, to match up why the rules are with what, because just memorizing it though that way doesn't really tell me why, you know. ... But I spent a week trying to figure out what I need to do and I still don't really know what I need to do.*"

An important source of Parker's problems with organic chemistry was the pace of the course, which was so fast that he felt it was impossible for the instructor to devote time to helping students understand the conceptual underpinnings behind why reactions occurred they way they did.

Organic students struggle because nobody teaches why, and the reason they don't teach why is because it would take too long. And they feel like they have to cram all this material in, and if you made this, you know, a longer class, or whatever, I feel like you could go so much more in depth, and you could understand why so much better, that you could be at that point right now at chapter 6 [instead of chapter 11], but know more than you do now.

It is important to emphasize that it was Parker's perception that the instructor did not teach the *why*. Our observations suggested that the instructor tried to do this, but the pace of the course was such that Parker could not develop the relational understanding he valued.

Parker was not the only instrumental learner in this study; the vast majority of participants in this study took this approach. Consider, for example, Francine's comments about the reaction of 2-methyl-1-butene with HBr, for which the possible answers were shown in Figure 5.

Back in high school, my chemistry teacher always tried to explain this [Markovnikov addition] to us. He was like, 'This is really grammatically incorrect, but, he who gots, gets.' *And we're like,* 'OK'. *It kind of stuck with me, so, it was whoever had the most hydrogen gets the H in the addition there.*

Or Jana's comments about the same reaction.

I just kind of know, I guess, freehand that in HBr addition that it's going to, a normal one is going to attach to the more substituted carbon. And since it's, I know the peroxide effect takes place with HBr, it kind of, it reverses the regioselectivity of the reaction to just something, pretty complicated explanation.

Although the students in this study were largely instrumental learners, they each acknowledged that they would really like to have a better understanding of the material. They indicated that the volume of the material, however, and the pace of the course were significant factors driving them toward instrumental learning. This is not surprising because these were the same factors that had previously been observed to drive students enrolled in general chemistry toward instrumental understanding (Carter, 1984).

Poor transfer from general chemistry

The transfer of knowledge has been defined as *"the ability to apply knowledge or procedures learned in one context to new contexts"* (Mestre, 2002). Transfer became an important issue in the analysis of interviews with Parker because of difficulties he encountered in applying knowledge learned in general chemistry to new contexts encountered in the organic chemistry course. His first interview clearly demonstrated that Parker had a good grasp of many of the concepts and principles covered in general chemistry. The second interview, however, suggested that he was not able to transfer these concepts to organic chemistry.

Furthermore, in much the same way that he had difficulty knowing which rule to apply in a given situation, Parker had difficulty selecting the appropriate conceptual knowledge to apply to a problem. Consider, for example, his approach to a question that asked him to determine whether HCl, H_3O^+ and BH_3 would react with propene in a manner similar to HBr. He successfully used his understanding of periodic trends to recognize that HBr and HCl might behave in a similar fashion.

Because you have hydrogen, same thing, and you have bromine and chloride, which are right next to each other in the same period on the periodic table of elements, so they're going to be similar compounds, like sodium and potassium are. They're going to behave the same way.

However, he placed H_3O^+ in a separate category, which he called the 'acid' category, and BH_3 in a third category.

And then the BH_3 is going to be out in its own little world doing its own little things with something completely new and different because the BH_3, the boron is just [sighs]. Boron the moron. It just does its own little thing, and I don't understand why for the life of me.

By concentrating on relationships based on the position of the elements in the periodic table, he overlooked differences in the relative size, electronegativity, basicity and other properties of elements in the same group that can lead to fundamental differences in reactivity. Furthermore, by focusing exclusively on trends based on position in the periodic table, Parker classified reactions as dissimilar when they are in fact quite similar. Thus, Parker saw H_3O^+ as a distinct entity when it actually behaves in a manner similar to HBr and HCl.

In his attempt to transfer what he knew from general chemistry to the problems he encountered in the organic course, Parker tended to focus on the properties of individual atoms or elements, rather than look at the structure and properties of a whole molecule.

You're not really good at chemistry until you understand what those elements are fully capable of doing. That's what things like organic, inorganic, physical chemistry, whatever those things might be, those are what they do. They give you, well this, you know, boron is so much more of a powerful atom that what you would have ever realized in gen chem. Let me show you how it does that.

Parker applied an approach to understanding organic chemistry that was an extension of a strategy that had been successful in general chemistry: focusing on individual atoms. In doing this, however, he failed to think about molecules as an organized whole. He seemed to view a molecule as a collection of atoms, which reacted more or less independently, rather than as a system of electrons.

"It gets me to the product"

In a study of the process graduate students use to solve organic synthesis problems, Bhattacharyya and Bodner (2005) concluded that:

> *If asked to distill the results of this study to a single sentence, we might respond: The curved arrows used in the electron-pushing formalism held no physical meaning for the graduate students involved in this study. Like the arrows drawn when equations are first used to represent simple chemical reactions, they were nothing more than a vehicle for getting from the reactants to the products* (p. 1405).

A similar phenomenon was observed in this study of undergraduates. Like so many of his peers, Parker focused on the products of a chemical reaction rather than the process by which the reaction occurred. During the second interview, for example, Parker discussed his answer to an exam question that asked students to predict the products that could be produced from an enantiomerically pure sample of the compound shown as the starting material in Figure 6.

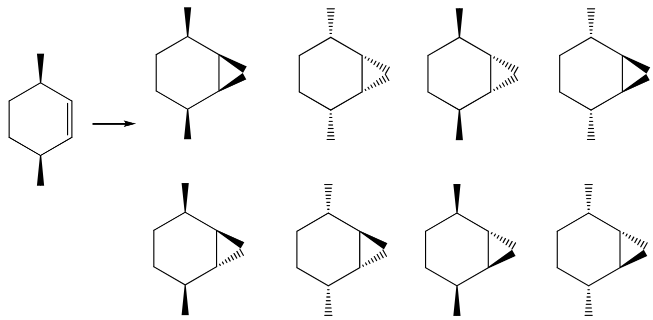

Fig. 6

Parker's strategy for solving this problem involved looking only at the reactants and products, rather than taking a mechanistic approach to the problem. *"So I said that whatever you're going to do, you obviously have to end up with CBr_2, because every single one [of the possible products] has to end up with CBr_2. So I knew that whatever happened, whatever the second thing did, the tribromomethane, that was going to do something. But I said the first thing [tBuOK] was pretty much inert. It wasn't going to do anything. It wasn't going to have any effect, cause you didn't see any effect from that on the rest of all these, like on any of them. ... And so, I just thought the potassium t-butyl oxide was in there going, look! I'm potassium t-butyl oxide. See you later."* Because Parker looked at reactions from a product- rather than process-oriented perspective, he didn't recognize the role that potassium t-butoxide played in the reaction; e.g., that the reaction could not occur if it wasn't in strongly basic conditions.

Stephanie's experience

It would be useful to compare and contrast Parker with another student in this study, 'Stephanie', who was by far the most successful student in this study. Although she also faced obstacles in the course, she was able to earn an 'A' and had, for a student at her level, quite a sophisticated understanding of the material.

Stephanie was different from the other participants in the study in several ways. First of all, she was able to use mechanisms to help her learn reactions, rather than thinking of reactions and mechanisms as two, separate and isolated phenomena. Second, she was able to see connections between different mechanisms that practicing organic chemists would view as similar. Finally, she was a self-regulated learner; she was able to let the material determine how she would best be able to study and learn.

On the surface, there was little that Stephanie 'did' on a day-to-day basis that was different from other students. But her attitude toward organic chemistry and her beliefs about organic chemistry lead to different results. If Skemp's (1979) model of an instrumental learner was appropriate for describing how Parker approached the learning of organic chemistry, then Stephanie might best be described as a relational learner. As was found in prior work in general chemistry (Carter, 1984), we concluded from this study that we need to find better ways of getting more students to approach our courses from the perspective of relational learners like Stephanie.

Concluding remarks

The students in this study provided living evidence of the validity of the notion that we can teach, and teach well, without having the students learn. We focused on Parker because he was such a good example of the phenomenon, but all of the students in this study struggled with organic chemistry in spite of being exposed to a course that we considered well-taught on the basis of what we observed by attending the lectures presented to the students. Several key points are important to recognize when considering the students in this class.

- We observed the instructor do what Parker wanted done — explaining the *whys* of organic chemistry.
- The textbook adequately and appropriated reinforced what the instructor did in class.
- Parker was a 'good student' in the sense that he attended class, read the textbook, and tried to do well in the course.
- We are convinced that Parker did not find what he was looking for in either the lecture or the textbook because the *whys* were communicated to the students in both lecture and the textbook through structures and mechanisms that utilized lines, letters, curved arrows, etc., that were not symbols for Parker because they did not symbolize anything that corresponded to physical reality for him.
- Although Stephanie also struggled with the course, she was able to see patterns in the organic chemistry course that Parker could not.

Although the goal of this study was to get a better understanding of the students enrolled in this organic chemistry course for chemistry majors, we believe our results provide hints of ways the typical organic chemistry course might be restructured to help overcome some of the problems these students — and so many others — face.

Students are introduced to the line structures with which organic chemists communicate toward the beginning of a typical organic chemistry course. They are then assigned homework problems that use these structures and little, if any, explicit attention is paid to the interpretation of organic structures as the course progresses.

The students are introduced to mechanisms in much the same way. They are told that the arrows represent the 'flow of electrons' and shown how to keep track of the locations of atoms and charges. After this brief introduction, they spend the remainder of the course learning specific mechanisms. Any problems that arise with students' mechanistic interpretations are assumed to be the result of difficulty with a particular mechanism, rather than difficulty with mechanisms in general. In our experience, it is rare to find instructors who devote extensive class time to developing an understanding of the reason why the electron-pushing formalism is used by organic chemists. The students often receive a hidden message that this is something that students should do when they first learn the subject, rather than a tacit message that this is something that practicing organic chemists do on a routine basis when they think about organic reactions.

The problem is simple: It takes a significant amount of time before line structures and mechanisms truly become symbols for students (Bodner and Domin, 2000). The interview data we have collected in this and other studies suggest that instructors need to spend more time explicitly drawing both the line structures with which they represent organic reactions and less condensed structures that show the atoms, bonds, and, in particular, the nonbonding electrons involved in the reaction, thereby freeing cognitive space for the students to attend to learning the conceptual basis of organic chemistry. Line structures are important because eventually they need to become symbols for the students. But drawing a fuller representation of the reaction can help the students focus on the chemistry to be learned, without struggling with first interpreting the meaning of the structures their instructor draws.

As a metaphor for what we are suggesting, consider what happens to students in general chemistry when their instructor uses the term *cation*. The student has undoubtedly encountered this term, and probably 'knows' what it means. But, when it is used in a new context many students have to momentarily pause in their thought process, to use some of their cognitive resources to interpret that it means a positively charged ion, before they can follow what the instructor is saying.

Now consider what happens when the instructor uses the phrase, *"... a positive ion or cation ..."* in the same context. More cognitive space is available to follow what the instructor is talking about, and less is devoted to fighting with the language in which the content is being delivered. Furthermore, by repeated use of this phrase, the term *cation* becomes automatically associated with the notion of a positive ion.

A similar phenomenon occurs in physical chemistry courses, where instructors are fond of talking about *adiabatic* processes, but rarely couple their use of this term with the tacit notion that students need to remember that these are processes for which no heat is exchanged between the system and its surroundings.

We also need to help students develop a deeper understanding for why they are expected to learn reaction mechanisms. The observation that Parker and other students in this study did not understand the purpose of mechanisms in organic chemistry is not surprising because other studies have shown that undergraduate chemistry majors (Ferguson and Bodner, 2008a, 20008b) and even graduate students in organic chemistry (Bhattacharyya and Bodner, 2005) have a poor understanding of the function of these mechanisms. It was clear to the first author when she attended the lectures for the two-semester organic chemistry course in which the students in this study were enrolled that their instructors told the students to use mechanisms to help them learn organic chemistry. But it was also clear that the students had not developed a deep enough understanding of the concept of a mechanism for these verbal appeals to be effective.

One approach to helping students understand the value of mechanistic reasoning is to provide them with in-class examples of problems that cannot be solved by resorting to memorization of rules. These could include problems for which no pre-existing rules exist and the students must instead rely on their ability to transform information from an earlier problem to the new problem. Or problems that require them to apply mechanistic reasoning to new situations (Bhattacharyya and Bodner, 2005). During these in-class problems, it might be useful to focus time on reaction intermediates to help students realize how mechanistic reasoning can help them predict possible competing reactions and understand the conditions that would favor or impede the formation of a particular product.

Our work suggests that it is a mistake to assume that students know how to approach the learning of organic chemistry because they have been successful in general chemistry. As noted previously, one of the reasons for focusing on Parker in this paper was the fact that he was an extremely successful general chemistry student who did not succeed in organic chemistry. It is possible that the reasoning process students develop in general chemistry might even hinder their performance in organic chemistry, if taken to an extreme. In general chemistry the focus is usually on individual atoms rather than an entire molecule. Reactions in general chemistry are seldom viewed in terms of a process. They appear to students as a 'black box' in which something new magically appears as one follows the arrow from left to right, whereas, in organic chemistry, attention is focused on how these molecular transformations occur. We need to be aware of the skills and ideas that students have taken from general chemistry and help them successfully apply these ideas in the new context of organic chemistry.

Most importantly, we have to recognize that having taught something is not the same as having the student learn what we have taught. That good students, doing what they believe should lead to success, may never see the 'big ideas' because of their struggle with the less consequential details of the courses we teach.

Several questions were raised while this paper was being prepared for publication. The first question asked: why didn't Stephanie have the same problems as Parker? We believe that the answer can be found in Skemp's model. As noted previously, there was little that Stephanie did on a day-to-day basis that was different from other students. As a relational learner, however, she was able to see connections that the instrumental learners did not, and she let the material determine the best way to study and learn.

The second question asked: is there was a way to convert instrumental learners into relational learners, or do we simply have to accept that students are either one or the other? This is a question that will be addressed in subsequent work. We can only suggest, so far, that our work with both general chemistry (Carter, 1984) and organic chemistry students suggests that it is far too easy to go in the opposite direction. Our work has clearly shown that the volume of material and the pace of a course can turn students who would prefer to be relational learners into instrumental learners.

References

Bhattacharyya G., Calimisiz S. and Bodner G. M., (2004), Strange bedfellows: organic synthesis and essay writing, *IEEE T. Prof. Commun*., **46**, 320-326.

Bhattacharyya G. and Bodner G. M., (2005), It gets me to the product: how students propose organic mechanisms, *J. Chem. Educ.,* **82**, 1402-1407.

Bodner G. M., (1986), Constructivism: a theory of knowledge, *J. Chem. Educ.,* **63**, 873-878.

Bodner G. M. and Domin D. S., (2000), Mental models: the role of representations in problem solving in chemistry, *Univ. Chem. Educ.,* **4,** 24-29.

Bradley A. Z., Ulrich S. M., Jones M. Jr. and Jones S. M., (2002), Teaching the sophomore organic course without a lecture. Are you crazy? *J. Chem. Educ.,* **79***,* 514-519.

Calimsiz S., (2003), How undergraduates solve organic synthesis problems. A problem-solving model approach, *Unpublished Master's Thesis*, Purdue University, W. Lafayette, IN.

Carpenter S. R. and McMillan T., (2003), Incorporation of a cooperative learning technique in organic chemistry, *J. Chem. Educ.,* **80***,* 330-332.

Carter C. S., (1984), A study of the relationships between spatial ability, sex, and success in general chemistry, *Unpublished Master's Thesis, Purdue University, W. Lafayette, IN.*

Chenier P. J. and Jenson T. M., (1983), Programmed study aids for solving problems in advanced undergraduate organic chemistry, *J. Chem. Educ.,* **60***,* 409-410.

Dougherty R. C., (1997), Grade/study-performance contracts, enhanced communication, cooperative learning, and student performance in undergraduate organic chemistry, *J. Chem. Educ.,* **74***,* 722-726.

Ferguson R. L. and Bodner G. M., (2008a), Making sense of arrow-pushing formalism by chemistry majors enrolled in organic chemistry, *Chem. Educ. Res. Pract.*, **8**, 99-110.

Ferguson R. L. and Bodner G. M., (2008b), Misconceptions held by chemistry majors while taking organic chemistry, *J. Chem. Educ.,* submitted for publication.

Gaddis B. A. and Schoffstaff A. M., (2007), Incorporating guided-inquiry learning into the organic chemistry laboratory, *J. Chem. Educ.,* **84**, 848-851.

Gosser D. K. and Roth V., (1998), The workshop chemistry project: peer-led team learning, *J. Chem. Educ.,* **75***,* 185-187.

Hass, M. A. (2000), Student-directed learning in the organic chemistry laboratory, *J. Chem. Educ.,* **77***,* 1035-1038.

Kampmeier J.A., Varma-Nelson P. and Wedegaertner D.K., (2001), *Peer-led team learning: organic chemistry*, Prentice-Hall. Upper Saddle River, NJ:

Katz M., (1996), Teaching organic chemistry via student-directed learning: a technique that promotes independence and responsibility in the student, *J. Chem. Educ.,* **73**, 440-445.

Libby R. D., (1995), Piaget and organic chemistry: teaching introductory organic chemistry through learning cycles, *J. Chem. Educ.,* **72**, 626-631.

Loudon G. M., (2002), *Organic chemistry*, Oxford University Press, NY

Meany J. E., Minderhout V. and Pocker Y., (2001), Application of Hammond's postulate: an activity for guided discovery learning in organic chemistry, *J. Chem. Educ.,* **78***,* 204-207.

Mestre J., (2002), Transfer of learning: Issues and research agenda, http://www.nsf.gov/pubs/2003/nsf03212/nsf03212.pdf, last accessed 5 November 2007.

Paulson D. R., (1999), Active learning and cooperative learning in the organic chemistry lecture class, *J. Chem. Educ.,* **76***,* 1136-1140.

Patton M. Q., (2002), *Qualitative research and evaluation methods* (3rd ed.), Sage Publications, CA.

Polkinghorne D. E., (1995), Narrative configuration in qualitative analysis, In J. A. Hatch and R. Wisniewski (Eds.), Life history and narrative, (pp. 5-23), Falmer Press, Washington, DC.

Schearer W.R., (1988), Beyond the traditional lecture system of teaching chemistry: organic chemistry, *J. Chem. Educ.,* **65**, 133-136.

Shane J. W. and Anderson T. L., (2007), Telling the whole story via narrative analysis, In M. Orgill, G.M. Bodner, Eds. *Theoretical frameworks for research in chemistry/science education*, Pearson Education Publishing, NJ.

Skemp R. R., (1979), Intelligence, learning and action – a foundation for theory and practice in education, John Wiley and Sons, NY.

Straumanis A. R., (2004), *Organic chemistry: a guided inquiry*. Houghton Mifflin, MA.

Tien L. T., Roth V. and Kampmeier J. A., (2002), Implementation of a peer-led team learning instructional approach in an undergraduate organic chemistry course, *J. Res. Sci. Teach.*, **39**, 606-632.