The instructor of an organic chemistry course describes in detail how he has used ideas about student motivation and self-regulated learning to change chemistry instruction at his university.

Progress in Practice: Using Concepts from Motivational and Self-Regulated Learning Research to Improve Chemistry Instruction

Brian P. Coppola

The tradition of active public discourse on chemistry teaching and learning began with the first contribution to the first issue of the *Journal of Chemical Education* (Cornog and Colbert, 1924). National and international meetings devoted to chemistry education have been held for nearly thirty years, and the first Gordon Research Conference on chemistry education was held in 1994. Very early in my experience as an organic chemistry instructor, I was drawn to a single phrase that made me believe that scientists other than chemists could have something to say about chemistry instruction and learning: "cognitive process instruction" (Lochhead and Clement, 1979). Since then, my classroom has been a crucible in which I have fused my knowledge of chemistry with the learning I have done in collaboration with researchers in education and psychology. Although there are other such individual efforts to bridge the gap between places in the university that are linked by their mutual interest in instruction, departments and schools of psychology and education remain fundamentally isolated from chemistry and the other arts, humanities, and sciences.

In this chapter, I report on how students in my content-filled subject matter course in introductory organic chemistry (called Structure and Reactivity) have benefited from their instructor's ability to recognize, translate, and contextualize notions from motivation and self-regulated learning; and I discuss a number of strategies that I use in my chemistry courses.

General Guiding Principles of Instruction

Four principles have guided my thinking as I have made changes in my instructional methods.

1. *Give out the implicit rules.* Every discipline creates linguistic and symbolic representations for concepts in order to facilitate communication. In professional associations, we share critical assumptions about representations and rules of operation used by our disciplines, including how these are connected to one other. Beginning learners in any area strive to build a picture based on necessarily incomplete information, and their understanding lacks the sophistication that allows experts to make judgments based on information that is only implied and not at all apparent in the surface features of any word, symbol, or action. The strategies outlined here all provide a way for students and faculty to check the progress of students' learning.

2. *Use Socratic instruction.* Anything that turns a passive listener into an active participant is a good thing. Unlike others who advocate dismantling the lecture classroom, I claim that what you do with your class time is the key. Certainly, a lecture to a group of novice learners cannot be like a professional seminar because the audience lacks all of the prior knowledge and shared assumptions and understandings of a professional group. However, it may not be necessary to demand individual accountability on the part of every student when a question is asked (as is the benefit in small-group work) but rather to give each student the opportunity to respond out loud to questions along with hundreds of others. I regularly teach in a 400-seat lecture hall. I do not need to hear every answer as I count to ten after asking a question, but instead, I want all of my students to understand that I want them thinking in their seats about the hour's topics and that I intend for all of them to participate. Some instructors make the error of only acknowledging the expected response among the noisy clamor, affirming the efforts of those who "got it right" without considering how and why other attentive learners could come to the "wrong" answer. I explore the range of possible solutions that students offer. That allows me to demonstrate the kind of reasoning skills I want the students to emulate. If I trust that the unexpected answer has been arrived at by some deliberate process, then I must deconstruct the argument to make the logical error appear; simply stating the correctness of an answer is always the easiest thing to do and the most comfortable for students who willingly accede authority, but it is the least constructive for learning. Another possibility among students who have very limited amounts of knowledge to draw from is that the "incorrect" answer is really quite reasonable and internally consistent with what they know at the time. Depending on the specific situation, I will either acknowledge the correctness of that conclusion as consistent within reasonable expectation, or I will use it as an opportunity to present new information. I ask open questions nearly every time I judge that I am making an informed decision, which makes the questions very brief, concrete, and focused rather than broadly philosophical. The opportunities to ask questions arise sponta-

neously, so they might occur three times in one minute or after a ten-minute monologue, but the effect is a kind of conversation between me and the class.

3. Create alternative metaphors for learning. When we instructors say "study, learn, and do problems," we do not account for the variety of strategies students have for studying, learning, and doing problems. I might memorize and recite lists of items as one way to learn if I judge that to be an appropriate strategy. But as an expert learner, I have developed a toolbox of techniques, and I readily create new tools as I need them, refining and discarding them according to the tenets of self-regulation. What do we mean when we say, "Do problems"? How can I express the difference to students who beat on every problem they face with the same wooden club, and who might easily look at one of my sophisticated, refined tools; pick it up; and start to hammer away with it too? One strategy is to use metaphor.

4. Make examinations reflect course goals. A set of examinations outlines the expectations, or goals, of a course much better than a syllabus. If these goals also include higher-order learning and thinking skills, then care must be taken to actively preclude unwanted skills. In other words, if I do not want memorization and recitation to be successful, then I must design tasks that do not reinforce these skills, and I must include explicit instruction for alternative strategies.

Specific Strategies for Active and Socratic Learning and Instruction

I use or suggest the following strategies very often because they are the kinds of skills I want my students to see me demonstrating and discussing in the context of the subject matter and that I want them to develop as habits as they learn.

Cognitive Modeling, or, Thinking Out Loud. I want to extend instruction from delivering knowledge alone to including how knowledge is created and used. This requires a great deal of reflection and introspection, as our own understanding of the most basic features of our disciplines is most often not explicit but rather a set of tacit assumptions shared by the professional community. This type of modeling by instructors helps students see others' risking, become metacognitively aware of their own ways of creating and using knowledge, and one hopes, begin to regulate their own thinking. I want students to see me take inventory of factual information, account for its limitations, and then draw meaning from the implications against the backdrop of my prior knowledge. Gorrell (1993) describes the advantage of providing implicit rules within a framework of cognitive modeling. One skill that students have rarely developed is the ability to suspend judgment while many possible interpretations are checked against the context of all given information. My students have a very strong need for one-to-one, logically dependent relationships: "Whenever I see 'H_3O^+' as a chemical reagent, what should I write as an answer?" The unsatisfying response, "It depends," describes how

we rely on the context: what else is around, what are the typical behaviors, and under what conditions do they occur? Students are uncomfortable with the uncertainty of science. How experts balance all of the information presented in a given situation needs to be explicitly modeled and reflected upon. The interpretation of spectroscopic data is another good example of a topic where a great deal of experience and unrepresented information needs to be unpacked in order to translate the lines and squiggles of a graphic output into an interpretation.

Using Analogies. Analogies are one of the most powerful tools we use in understanding. Analogies presume the interconnected nature of knowledge, because we seek to make the unfamiliar comprehensible in terms of a relationship to our prior knowledge. The habit of creating analogies stands out as the most identifiable outcome of my own graduate training. Whether I encounter a new chemical reaction described in a chemistry journal or an unfamiliar notion in educational psychology, my instinct is to presuppose a connection to something I know and to wonder out loud, "What is this like?" For students, analogies can fulfill two roles. At the beginning of a course, they can connect new concepts from an unfamiliar discipline to students' previous experience ("When the two molecules collide, three of the groups attached to the carbon atom unfold and invert like an umbrella in the wind"). Later in the course, lateral connections can be made by grouping similar ideas together ("When they undergo collisions, the atoms in the following set all behave like the carbon atoms you have learned about already"). Another common verbal exchange in my class starts with this question: "If I use [this]$_a$ as an analogy, what do I expect? And if I use [this]$_b$ as an analogy, what now?" After exploring the logical consistency of the responses, I discuss how to decide which analogy is most appropriate, after which the design of experiments to test alternative interpretations becomes meaningful.

Using Counterintuitive Examples. I understood the value of counterintuitive examples in a Socratic environment the first time 300 students all yelled out, with great confidence, the "wrong" answer. These situations occur when students use uninformed models to make decisions. The counterintuitive example is really nothing more than the usual laboratory observation of an "unexpected result." For example, a common correlation discussed in introductory chemistry is that of the observed hydrogen ion acidities for bonds derived from atoms within the same row of the periodic table with the trend in the property known as electronegativity. In chemistry, there is a great tendency to use causal language ("the trend in acidity is *due to* electronegativity") rather than correlative language ("the trend in acidity is correlated with electronegativity"). Students, who seem to prefer simple, universal models, will extrapolate this causal language to all acidity relationships. So when students are asked to predict the relative acidities of similar molecules made up of atoms from a column of the periodic table, they use the electronegativity model easily, consistently, confidently, and vocally. This is an appropriate example of making an analogy, after all. Unfortunately, the experimental result in this case

is just the opposite from the prediction. That does not make the prediction wrong, because the model is being used correctly. It is simply a reflection of scientific practice according to Thomas Henry Huxley: beautiful theories are killed by ugly facts. Although there is a danger that some will become relativists, many students seem to learn from these examples how and when people need to increase the factors to which they attribute phenomena. After a few rounds of examples such as this one, applied liberally at the beginning of the course, the class starts to develop a healthy skepticism about my questions. I am exhorted to "give out the experimental result," or I might get more conditional answers: "If it turns out this way, then this factor must be more responsible than that one. . . . If it turns out the other way, then . . ."

Providing Heuristics. Providing heuristics is an aspect of cognitive modeling that deserves its own mention. In every subject, we have personally meaningful learning tools or strategies that allow us to make decisions or recall information and relationships more easily. In organic chemistry, one of these tools might be the way I decide which of six outcomes from four possible reaction pathways might be expected to occur. Concept maps can help the instructor and the student represent such information and externalize the ideas for better discussion (Novak and Gowin, 1984; Markham, Mintzes, and Jones, 1994; Nakhleh, 1994; Pendley, Bretz, and Novak, 1994). Mnemonics are another useful tool (Fieser and Fieser, 1956, p. 359; Williams, 1992).

Changing Teacher/Student Roles. One of the most startling revelations for my students occurs when they realize that our roles explicitly reverse during an examination. As the questioner, I am now going to them for advice on how to solve a problem. For those ninety minutes, they need to see themselves in the role of the instructor, to engage in the kinds of behaviors they would while working with their friends or study group partners rather than to think of themselves as the repository of prescribed answers. Examinations are to be engaged actively, and by having the reversal of roles pointed out to them, students can appreciate the value of working with others before an exam. One way or the other, we instructors demand *performance* on an exam, and the worst time to consider the ins and outs of articulation for the first time is during the exam itself.

Using New Metaphors for Teaching and Learning. Students need help in understanding the role metaphors play in shaping disciplines and how metaphors can help them in their own learning.

The Narrative of Science. The concept that all disciplines are sophisticated narratives created by humans is not appreciated very well by students. The rhetoric of moving naïve objectivist notions to more constructivist epistemologies currently occupies a central position in science education research (Garafalo and LoPresti, 1993; Roth, 1993). Careful attention to language in our classes can, I believe, help students understand these ideas. I never miss the opportunity to use the expression "telling a story" when I provide chemistry's rationalizations for phenomena. To support this viewpoint, I bring in quotes from external sources, including the article title "Telling the Stories of

Educational Psychology" (Berliner, 1992) and the following observation by Ackroyd (1989): "Science is like fiction, you see. We make up stories, we sketch out narratives, we try to find some pattern beneath events. We are interested observers. And we like to go on with the story, we like to advance, we like to make progress. Even though they are stories told in the dark" (p. 159). On occasion, at the beginning and then at the end of the year, I have asked my students to complete the following assertion: "Chemistry is a science where . . ." At the beginning of the year, in general and overwhelmingly, students write: "Chemistry is a science where atoms and molecules are studied." By the end of the year, nearly all of the responses carry interesting and sometimes profound perspectives: "Atoms and molecules may be the building blocks of matter, but there is no cohesion, that is, the 'big picture,' without chemistry."

The Performance Studio. Most instructors encourage students to work with each other for a variety of reasons, but the common thread that runs through these rationales is the same: you really learn the material when you have to teach it. I assert that a broader reason is imbedded here, one that comes very naturally to disciplines such as art, theater, and dance in which *performance* is explicitly recognized as the way individuals regulate their learning. In these disciplines, we understand the role of performance as we learn, and our perspective on learning is always cognizant of our need to share what we have learned with others. Evaluating task performance is at the heart of examinations. I further assert that learners who take their need to articulate into account, by whatever method is required by the context, are doing more than just enacting their skills, they are also anticipating the teaching aspect of their learning. Learning to solve chemistry problems, then, is metaphorically related to the studio time required in an art or music class. This is a notion that can be easily shared with and understood by students.

The Persistent Learner. Persistence is a key outcome of motivated learning. One belief that I want to support is the idea that learners always construct their understanding by seeking and creating larger patterns (the "big picture"), by grouping, ungrouping, and regrouping the interconnected individual ideas. There is a great deal of intellectual risk, at the cost of ego, in backing away from a perceived pattern, even if all of the pieces do not quite fit. (What is even worse is to believe that you are simply not capable of seeing any pattern at all because of a fundamental inadequacy. Then there might be a conscious decision to not invest the energy to persist, and that is a different situation.) But I have observed very capable students who seem to lack the awareness that they must actively move back and forth between smaller and larger concepts, constantly checking and rechecking the internal consistency of the picture they are constructing.

Using Texts in a Self-Regulated Manner. My experience with chemistry students and textbooks is discouraging. I have asked students to describe their textbook habits many times, and the majority of them read their texts as they might a novel, in a linear deliberate march that presupposes that every nuance on page 251 needs to be assimilated before they go on to page 252. Not sur-

prisingly, the contextualized problems within a chapter are always "easier" than the uncontextualized ones at the end of the chapter, and a significant number of students simply treat the worked-out answers for the latter in the answer manuals as another kind of text, to look at, outline, and highlight. Alternative strategies for using textbooks can be suggested. Here are two examples:

First, tell students to "sketch out" their understanding by concentrating on what they can understand as a starting point. I remind students to treat chapters as whole units, and I recommend multiple cursory passes through the information in order to get a feel for the broad context and to look for repetition in the discussion. As in painting a portrait, it is a bad idea to articulate any one feature with too much detail too early—the perspective and proportion of the whole picture will tend to distort around that feature. Instead, painters first sketch and then incrementally refine, always with an eye on relationships between details and the whole.

Second, tell students to "separate reading time from problem time and think about starting with the problems." By starting with the problems, a student can begin to make discriminations about the information in a text. But this does not mean searching for the appropriate pages to solve the problem; it is, rather, just getting a sense of the ideas. Linking a problem with the reading about it creates a context, but is not a very useful skill to take into an exam. Students need to be explicitly reminded of the value of learning that they do not yet have enough information to categorize or solve a problem. They need to know that an important way to gauge their level of understanding is to admit what they can and cannot do. This type of textbook learning is much more in line with a self-regulated learning approach to reading texts than is the linear and deliberate type.

Changing Exam and Grading Policies. When those of us teaching chemistry examined how to achieve departmental goals in the introductory organic chemistry course, we recognized that organic chemistry was structured in such a way that state-of-the-art information, derived from the primary literature, could be presented to novice students on their examinations. This strategy assures us that we are being honest to the actual facts of science and not simply inventing trivial derivatives of classroom examples. Each citation from the primary literature is accompanied by some contextualizing statements. The citations send two messages to the students: first, that just memorizing all of the textbook examples is not enough and, second, that understanding the subject matter of the introductory course allows them to understand some of what chemists actually say about the things they study. The contexts of these problems carry a great deal of intrinsic interest, or relevancy, because many of the examples come from the areas of medicinal and pharmaceutical chemistry or materials science. In a sense, the examination questions I use are like short case studies.

I also reinforce the idea of multiple representations for the same phenomenon. A student might be asked to provide word, picture, and numerical versions of the same idea. There are many times when there are four, five, or

more correct solutions within the context of the course and the information provided in a question. On nearly every exam, students suggest completely reasonable alternative solutions that I did not anticipate. These are also important lessons for instructors to make note of as they teach their classes.

Finally, because students develop their new skills at different rates and because the course is truly cumulative each step along the way, those of us teaching chemistry have devised ways to make improvement count. One simple but effective technique is increasing the point value of exams throughout the term without increasing the length of the exam. It is "worth" more to do better later, so students do not feel they have to be perfect at the outset, and their practice has tangible value for them. I also make judgments about improvement by considering the set of exams and the final as two independent measures of cumulative performance. Herschbach (1993) keeps an account of the points lost during the term as a function of topic. Students who master these topics on the final have their earlier points "resurrected" in an accounting of their grade.

Conclusion

Education is not a neutral activity, and it is a collaborative process. As instructors, we all are changing the way our students think about the world, and we are interested in assisting the change in a productive way. We can learn a great deal by listening and watching our students carefully as they learn. At the outset, instructors should establish an explicit and common agenda of instructional goals with their students, so that everyone is working toward the same end. Otherwise, the intrinsic cognitive dissonance will always put instructors and students at crossed purposes.

I have spent over ten years grappling with the implications of what psychology and education have to say about instruction and learning. I have discovered that ideas from motivation and self-regulated learning can play a significant role in the instructional design of real classrooms comprising hundreds of students taking introductory chemistry. The development of ideas needs to flow in both directions: between the pedagogical content knowledge of the instructor as an expert in his or her field and the theoretical constructs of education and learning research.

The implementation of the strategies I describe here has been integral to the structure of the course. As one of my students remarked last year, "You know what's nice about this course? Not only is it obvious that you have an instructional plan, but you have also let us in on it." From my viewpoint, three lessons from my experience with the design and implementation of the introductory organic chemistry course stand out.

First, instruction that encourages students to develop higher-order skills is best accomplished within a well-defined discipline from which the contextualized expertise of faculty can be drawn. I am a trained organic chemist, and the pedagogical content knowledge (Clermont, Borko, and Krajcik, 1994) I bring to this course allows me to construct the most meaningful kind of learn-

ing environment for my students. The notions of "anchored," or "situated," learning ring true and argue against the general survey course (Brown, Collins, and Duguid, 1989; The Cognition and Technology Group at Vanderbilt, 1990, 1992; Lave and Wenger, 1991). In addition, my experience shows that ideas about motivation and self-regulated learning can be used in a content-filled class. They do not have to be used only in generic learning and thinking skills classes.

Second, new faculty can adapt to very different instructional environments than the ones they have known and contribute in positive, creative ways if a system of education and support is created. In many ways, the same techniques instructors use to make instructional goals and strategies explicit for their students can be used to engage faculty.

Third, the concept of collaboration across the university in order to advance instruction and learning makes sense. I am sure that our students who report that they "certainly learned more than chemistry" are reflecting the practical benefits of theoretically sound design. My colleagues in chemistry, psychology, and education are actively pursuing these leads with me.

References

Ackroyd, P. *First Light.* New York: Grove Weidenfeld, 1989.

Berliner, D. C. "Telling the Stories of Educational Psychology." *Educational Psychologist,* 1992, *27* (2), 143–161.

Brown, J. S., Collins, A., and Duguid, P. "Situated Cognition and the Culture of Learning." *Educational Researcher,* 1989, *18* (1), 32–42.

Clermont, C. P., Borko, H., and Krajcik, J. S. "Comparative Study of the Pedagogical Content Knowledge of Experienced and Novice Chemical Demonstrators." *Journal of Research in Science Teaching,* 1994, *31* (4), 419–441.

The Cognition and Technology Group at Vanderbilt. "Anchored Instruction and Its Relationship to Situated Cognition." *Educational Researcher,* 1990, *19* (5), 2–10.

The Cognition and Technology Group at Vanderbilt. "The Jasper Series and an Example of Anchored Instruction: Theory, Program, Description, and Assessment Data." *Educational Psychologist,* 1992, *17* (3), 291–315.

Cornog, J., and Colbert, J. C. "What We Teach Our Freshman in Chemistry." *Journal of Chemical Education,* 1924, *1* (1), 5–12.

Fieser, L. F., and Fieser, M. *Organic Chemistry.* (3rd ed.) New York: Reinhold, 1956.

Garafalo, F., and LoPresti, V. "Evolution of an Integrated College Freshman Curriculum: Using Educational Research Findings as a Guide." *Journal of Chemical Education,* 1993, *70* (5), 352–359.

Gorrell, J. "Cognitive Modeling and Implicit Rules: Effects on Problem-Solving Performance." *American Journal of Psychology,* 1993, *106* (1), 51–65.

Herschbach, D. R. "Paradigms in Research and Parables in Teaching." *Journal of Chemical Education,* 1993, *70* (5), 391–392.

Lave, J., and Wenger, E. *Situated Learning: Legitimate Peripheral Participation.* Cambridge, England: Cambridge University Press, 1991.

Lochhead, J., and Clement, J. (eds.). *Cognitive Process Instruction.* Philadelphia: Franklin Institute Press, 1979.

Markham, K. M., Mintzes, J. J., and Jones, M. G. "The Concept Map as a Research and Evaluation Tool: Further Evidence of Validity." *Journal of Research in Science Teaching,* 1994, *31* (1), 91–101.

Nakhleh, M. B. "Chemical Education Research in the Laboratory Environment." *Journal of Chemical Education*, 1994, *71* (3), 201–205.

Novak, J. D., and Gowin, D. B. *Learning How to Learn.* Cambridge, England: Cambridge University Press, 1984.

Pendley, B. D., Bretz, R. L., and Novak, J. D. "Concept Maps as a Tool to Assess Learning in Chemistry." *Journal of Chemical Education*, 1994, *71* (1), 9–15.

Roth, W.-M. "In the Name of Constructivism: Science Education Research and the Construction of Local Knowledge." *Journal of Research in Science Teaching*, 1993, *30* (7), 799–803.

Williams, J. P. "A Mnemonic for the Krebs Cycle." *Journal of Chemical Education*, 1992, *69* (12), 985–986.

BRIAN P. COPPOLA is lecturer in chemistry and coordinator for undergraduate organic chemistry curriculum at the University of Michigan, Ann Arbor.