Students' Reasoning and Rhetorical Knowledge in First-Year Chemistry

Linda Driskill, Karen Lewis, Jennie Stearns and Tracy Volz
Rice University

Abstract

A case-based introductory chemistry course at Rice University tests students' reasoning with essay questions. A protocol analysis project investigated the relation between successful and unsuccessful students' reasoning about chemistry and their rhetorical knowledge. We observed that (1) students' writing processes were affected by several constraints (time, accessibility of information in memory, need to repress dissonance, design of the exam, knowledge of test answer genres, and predisposition to enact test-taking roles learned in high school), and that (2) writers' rhetorical knowledge influenced their ability to reason and discuss chemistry. Theories of analogical reasoning helped explain differences in students' reasoning and performance. A complex model that includes components representing genre and role was created for explaining the composing processes needed in writing answers to ill-defined problems. Recommendations for new uses of writing in introductory chemistry were developed, based on the differences observed in successful and unsuccessful writers' processes.

New emphasis on theory and reasoning

At the third national Writing Across the Curriculum Conference (1997), keynote speakers warned of several trends rapidly sweeping higher education and emphasized universities' need to prepare students to accept change and solve complex, non-routine problems. So quickly are the challenges in the workplace evolving that futurists expect sixty percent of the jobs available in 2007 will be ones not yet invented today. Many introductory chemistry courses shortchange students by teaching standard procedures for routine problems. To meet the more complex challenges looming ahead, students should be learning how to define complicated problems, evaluate models for solving them, use genres, adopt roles, and communicate with others who may share responsibility for addressing problems. Emphasis on formulas and calculation, especially in scientific fields, has repressed discussion of problem solving's rhetorical dimension.

One non-traditional course, John Hutchinson's Chemistry 101 at Rice University, presents first-year chemistry as intellectual inquiry; the course's central feature is argument and explanation to others. His textbook explains, "The models, concepts, and theories we use to describe nature are accomplishments equal in creativity to any artistic, musical, or literary work. Unfortunately, textbooks in Chemistry traditionally present these models and concepts essentially as established facts, stripped of the clever experiments and logical analyses that give them their human essence" (Hutchinson, *Cases*, iv). Hutchinson's students experience the challenge of creating new knowledge as they participate in classroom dialogues concerning nine historical cases (method described in T. A. Holme). The cases recreate the uncertain situations faced by chemists of an earlier time and challenge the students to design experiments, propose theories, and test hypotheses that led to revolutionary insights.

The reasoning and writing required in Hutchinson's chemistry course, particularly in its examinations, differ significantly from the cognitive demands described in Coppola and Daniels' first year chemistry course (69, 81). Their students' writing primarily consists of comparison, summary, and definition. In contrast, Hutchinson's students write to test theories and respond to ambiguous situations. Hutchinson's approach has special value because it involves students in writing and problem analysis early in their college careers and sets up expectations for the kind of work students would perform in the future as chemists.

Students participate in group problem solving in class and have an opportunity to address theoretical issues individually on exams which both majors and non-science majors have been able to pass in the past. In addition to traditional chemistry problems, Hutchinson's exams contain multi-part essay questions of the following types:

Question Type 1. identifies a theory and asks students to present experimental evidence that would support the theory,

Question Type 2. provides experimental observations and asks students to explain the theoretical conclusions that can be drawn from them, or

Question Type 3. presents two seemingly contradictory observations and asks students to use a specified model to resolve the contradiction.

Students receive limited instructions about tests in advance. They are not taught about these three question types, but they are given explicit advice about audience. Hutchinson says, "I tell them . . . . You have to assume that the reader is very smart; capable of understanding your answer, well informed, but you have to explain it" (Interview). A good answer, Hutchinson and his graders claim, is one that would make sense to a fellow student. Because students must cast their understanding in words rather than formulas and because the information must be expressed in logical propositions for a smart novice, the rhetorical aspects of problem solving are foregrounded. In effect, Hutchinson says, a student writer should become a teacher.

In the fall of 1995, a higher proportion of student writers who claimed to "know the material" were having trouble with the essay questions on the first two tests. Students sometimes confused *information* with *argument*. When students came to Hutchinson unsure why their answers had been marked wrong, he said, "The first complaints . . .were always in the nature of 'my answer's the same as hers, but I got counted wrong,'" (Interview). In other words, even after receiving their graded exams, students were having difficulty recognizing the differences between a memory dump and an answer that actually explains connections between facts. To understand the differences in writing processes that led to misunderstanding the requirements of examination writing, a research project, described in this paper, was created. The study led to recommendations for using writing to learn and solve problems characteristic of chemistry research that involves major discoveries.

Investigating the relation of reasoning to rhetorical knowledge in chemistry

A team from Chemistry and English compared the essay test writing strategies of successful and unsuccessful students, and more fundamentally, the relation between their reasoning about chemistry and their rhetorical knowledge. Protocol analysis, which has been used to study problem solving in other fields, especially mathematics, as well as writing processes, was chosen as a method (Flower and Hayes; Flower, *Construction*, 317-329). In protocol analysis, a writer speaks aloud as he or she solves a problem, and the remarks are tape recorded, transcribed, and analyzed along with the drafts. This process cannot capture all of the writer's cognitive processes, but it allows researchers to glimpse many significant actions not evidenced in the final text.

This method was used with nineteen students who were invited to take a practice test (Appendix) before the final one-hour exam of the semester. All of the students but one (who spoke English as a second language) talked freely while being recorded. In most sessions, an observer watched and prompted students if they fell silent for several seconds. Half of the remaining eighteen students (9 men; 9 women) had received A's and half had received D's or F's on the two previous exams. Experienced Chemistry Department graduate students graded the practice exams, and the English Department team analyzed the transcribed recordings.

Elaborating earlier models of writing to explain examination writing

We elaborated the sociocognitive model that was developed by the national Center for the Study of Writing (CSW) between 1985 and 1990. CSW studies emphasized that social influences and prior experience play forceful roles in writers' or readers' task representations and constructions of purpose. However, the categories used for analyzing writing processes in these studies were not sufficient to capture differences between successful and unsuccessful writers' processes.

Nelson's CSW study spotlighted the persistence of students' prior experience and familiar writing strategies in task representation. She also described the discrepancies between the tasks instructors believed they were assigning and the tasks students represented to themselves. Behaviors and text features rewarded in a particular setting significantly affected students' interpretations of an assignment and shaped their approaches (Nelson 20). She concluded that teachers were too likely to expect novices to figure out field-specific ways of thinking and writing suited for sociology, engineering, and so on. Unless motivated, students could reduce assignments to a system of production shortcuts without engaging with the central issues of the course.

In another CSW project, Stein and Flower studied the task representations and strategies of college freshmen in "reading to write" tasks. The "reading to write" project analyzed cognitive processing into four categories: planning, monitoring, elaborating, and structuring. In "elaborating," Stein suggested, prior knowledge combines with source text propositions to create new ideas and critical perspectives. On the other hand, "structuring" involves "looking for instances of agreement and disagreement between propositions in source texts or between a proposition in the source text and the student's prior topic knowledge, looking for superordinate categories under which to subsume items in the source text, arranging text into high-level and low-level propositions, and discovering relations between ideas in the text that may not have been apparent on reading alone" (Stein 3).

Despite their relevance to task representation, these four broad categories of cognition were not specific enough to account for differences between successful and unsuccessful chemistry reasoning or writing. They left a good deal unexplained about the relation between memory searching, planning, and drafting. Most protocol studies have assumed memory searching is an unproblematic activity. In test-taking, however, the role of memory searching becomes critical, and each of these four activities change a great deal from their manifestation in paper writing: planning drops to zero, structuring becomes a controlling factor as the question is reformulated as a "thesis" that guides drafting, and "elaborating" becomes recall of information plus some commentary. Monitoring is reduced to a minimum—even watching for typos and grammatical scanning may be abandoned. Even more, these categories did not account for larger issues of academic role, purpose, and genre. We wondered why, after students had attended 30 hours of class and taken two exams, most did not immediately notice when once again Professor Hutchinson gave them pairs of discrepant observations that were to be explained in terms of a particular theory or model.

Relevance of psychological theories of analogical reasoning to writing

We supplemented the categories of cognitive processing with codes based on psychological theories of analogical reasoning, social construction of knowledge (Bazerman), and genre (Berkenkotter and Huckin). As the following discussion will show, their primary value is to describe more adequately the processes of task representation and construction of purpose. They provided the basis for describing differences in memory search processes, comparisons, and logical reasoning. They also helped us to describe the roles students assumed in particular writing situations.

Three theories of analogical reasoning have become dominant—cognitive mapping theory, constraint theory (which involves the role of context and pragmatics) and case-based reasoning theory (Gentner and Holyoak; Holyoak and Thagard; Kolodner). The three theories share fundamental assumptions whose stability has been well established, according to Gentner and Holyoak (32). Each of the theories helps explain specific aspects of the complex reasoning and writing required in Hutchinson's tests. We will first explain the relevant aspects of each theory.

Holyoak and Thagard (35) illustrate the central processes of cognitive mapping in analogical reasoning with the behavior of little Aaron, aged 24 months. Like other toddlers most people have known, Aaron was in the habit of coming to his mother when he experienced some hurt so she could "kiss the boo-boo" and "make it better." Unexpectedly, as she was dressing him one day, Aaron's mother exclaimed that her hand hurt. Almost instantly Aaron responded, "I kiss it."

In this story little Aaron draws on such incidents, called "source analogs," to define significant features of a new situation, a "target analog." This process has three steps: (1) perception of similar features in the source and target (a child and a mother in the example); (2) recognition of similarities in relationships or categories (an injured person and a family member); and (3) assignment of structural similarities in roles (one who presents an injury; one who administers the soothing kiss). The process of constructing the analogies is called mapping.

Holyoak and Thagard point out that little Aaron might have found corresponding features and relationships in the situation without choosing a new role for himself (he could have "mapped" or identified his mother in the source analog with his mother in the new situation). In that case, he could have said, "Mommy, you kiss your hand." However, he did not do this; he mapped the role of the injured person in the source analog onto his mother in the target situation and assigned the role of caregiver (his mother in the source) to himself.

Indexing and mapping to detect "role relationships"

What makes Aaron's performance possible? Case-based analogical reasoning theory would explain that Aaron's earlier experience had become "indexed" in his memory so that he could compare situations through mapping. When it comes to learning in school, students may have too few experiences to enable them to draw on their backgrounds in solving some problems; they lack a source analog to apply to the item in the test (Kolodner, 57-58). And their assigned reading may not be helpful because they did not "index" features for reference as they read and did not look ahead to anticipate how the reasoning or elements could be used in the future. A mass of unindexed reading doesn't help students much on a test: some try to memorize, as a whole, a long stretch of material but cannot search it. In addition, the questions asked in traditional tests train students to look for mere matching or one-to-one feature correspondence, the kind of question that would ask little Aaron to recognize "mother" in both situations.

Reasoning for a purpose and to achieve coherence

Constraint theory contends that how analogical reasoning proceeds depends on three powerful influences: the proportion of one-to-one feature correspondences that can be observed in the source and the target, the felt need for coherence between the source and the target, and the purpose of the reasoner in making the analogy (Holyoak and Thagard). Aaron's purpose and social context were stronger constraints than the need for congruence between categories. In exam situations, the time limit serves as a high pressure constraint. The greater a student feels the need for coherence, the more he or she is likely to ignore differences between the source and target, differences Hutchinson wants students to explain. Furthermore, if a memory search yields meager results, any perceived correspondences may seem like a high proportion of correspondences worth writing down. Constraint theory helps explain how the role proposed in mapping theory can be so powerful, bringing to bear the individual's purpose and other contextual factors. It also helps explain why some analogical reasoning in test taking concludes prematurely.

Reasoning that adapts old knowledge to new situations

Case-based analogical reasoning theory explains how prototypic experiences or cases may be revised or reindexed and applied to novel problem-solving situations. In courses that teach case-based reasoning, Kolodner (62-64) explains, students address complex real-world problems by applying prior knowledge, however indexed. To prepare for applying knowledge, they need to have recognized multiple possible implications of concepts studied prior to actually taking a test. Otherwise, when an exam poses a new problem to which a learned case study might be relevant, students are not likely to realize—or even remember—which memorized concepts will help them solve this new problem.

In searching for feature correspondences and looking for sets of relationships during a case project, students can qualify, limit, or complicate their prior indexing. Hutchinson helps students index classroom cases by involving them in classroom dialogue; the exam writing causes reindexing and more robust learning. Students taking tests are asked to recall a previously indexed theory and relate it to appropriate theoretical evidence; to compare experimental observations to theoretical concepts in order to draw conclusions, or to resolve apparently contradictory observations by means of a specific theoretical model. In writing, students reindex and complicate their understanding of chemistry and achieve a higher level of cognitive flexibility, becoming able to adapt concepts to a variety of situations.

Analogical reasoning involved in chemistry exam writing

Analogical reasoning is likely to be involved when students

- read and interpret questions
- search memory on the basis of indexed terms
- select models or concepts related to key terms
- assign relationships (sometimes called roles) among items in a narrative of events
- reason about the relation between theory and observations
- assume social or disciplinary roles in writing

Students recognize feature correspondences as part of the cognitive process of reading test questions. For example, when students see key terms, such as "valence," networks of indexed terms are activated in their memories. Some questions may force students to relate specific words or phrases to an appropriate set of concepts (as when they are told to explain a specific observation in terms of "the nature of radiation"). When they recognize the correspondence, students say "Oh, now I get it" or "I see what he's asking me." However, in Hutchinson's questions a word may relate to more than one model or concept set. In the following excerpt, the instructor had intended the student to reject one particular model, the Lewis structure model, instructing the student: "Explain each of the following observations *in terms of the properties and energies of the occupied orbitals in the valence shell*" (Question 2, Appendix, emphasis added). However, in the following protocol excerpt the student disregards the instruction and relates the term "valence" to the Lewis structure model anyway, telling the tale of "what calcium 'really wants'" instead of relating it to atomic shell theory:

> . . . if potassium were to give up one of its electrons, it would attain a full outer shell. It would have an electron configuration of argon, and basically most atoms are trying to attain a full outer shell (Student 19).

Because "valence" occurs in both models, the student makes a common error. The student's sense of urgency in the test situation and the apparently adequate one-to-one correspondence between a term in the question ("valence") and a term indexed in memory apparently causes the student to settle for the first correspondence he recognizes instead of looking for other correspondences based on the instructions. Hutchinson commented that this particular error occurs frequently.

The writer's role also drives the reasoning and writing processes by affecting task representation. Bazerman contends that the classroom is a set of scenes for writing, each with its expected student roles and genres. Hutchinson's tests demand that students play a role quite different from the one most students had known in high school. Although he had told his students to imagine themselves *teaching* other students with their answers, most chemistry students did not escape the role of the one being interrogated: "So what are they asking me to say? (rereads the question) OK. That's kind of vague. I think I'm just going to start writing, because if I show him I know something, it's better than showing him I know nothing." This woman remains in the student role of one being told to speak and proceeds in ways she thinks will be rewarded, just as the students Nelson studied did (22). And indeed, the student's perceptions coincide with the graders' own accounts of how they allocate points (Interview with graders). Both settling for identifying one-to-one feature correspondences and settling for a familiar student role led test writers to produce less satisfactory answers, to do what would earn some points but less than a maximum score.

Changing writing roles is not easy. Student 4 commented: "It's kind of shocking to come here and see a different format for taking tests. In high school, basically all you needed to [do] was memorize, try to understand a little bit of the background, two or three essay questions, and the rest was multiple choice or fill in the blank. . . . But here, when you study, it's totally different." Student 1 had abandoned his high school approach: "I took the first test, and I decided I was doing something wrong. I needed to step up to a higher level there, because I wasn't internalizing the information. I was basically just trying to spit it back, and it didn't work . . . ." Memorizing the case itself also was inadequate, Student 1 said, ". . . because I know they have questions on the test that don't directly apply to the cases in the book sometimes. You are just supposed to infer this from that over there." Student 1 is informally describing the mapping that must go on from the source to the target analog.

As Student 1 notes, analogical reasoning in Hutchinson's chemistry tests demands that students juggle several constraints: time, varying levels of indexed concepts and information in memory, and the pragmatic issues of graders' practices. Hutchinson's first question type identifies a theory and asks students to present experimental evidence that would support it (such as Question 1b in the Appendix). The student must be able to recall indexed examples or types of appropriate evidence. Hutchinson's Type 2 questions, such as 1a (see Appendix), provide a key term: "Explain briefly how we can account for these observations in terms of the nature of *radiation*." The student must have indexed the term "radiation" to related definitions and concepts and must be able to map that knowledge onto the details or observations about the photoelectric effect (See question 1a in the Appendix). Some questions could possibly require several analogic reasoning steps.

The mapping function required in question 1a ("explain in terms of *radiation* . . . ") does not really position the student in the teacher's role as Hutchinson intends. Although Coppola and Daniels (77) like Hutchinson say they want the student to teach others with their answers, "becoming the teacher" is a complex role change. The test question does not give the student the freedom to choose the source analog needed to occupy the teaching role. Most adult roles, not just teaching roles, usually include the authority to choose one's own source or target analogs.

"Teaching" for the purpose of our analysis means presenting information or arranging for students to encounter the information in a way that leads to indexing. When students become "teachers," they demonstrate the definition and logical significance of material while using a genre the field considers appropriate. They also demonstrate their ability to connect concepts with indexed terms, manipulating source and target analogs. And most challenging of all, they must select the appropriate starting points for their audiences—other students. Many students seem to disregard the instruction to teach, possibly because they are so overwhelmingly conscious of their own role as the ones being interrogated.

Students in the chemistry course did not recognize the "teaching" role implied or genres of answers they should produce. Because Hutchinson does not explicitly go over the three "types" of questions that regularly appear on his chemistry tests in class, students don't recognize them as writing genres. Miller describes a genre as "typified rhetorical actions based in recurrent situations" (159); Bazerman elaborates genre as "a social construct that regularizes communication and relations" (62). According to Patrick Dias, his students' lack of genre knowledge in Education caused them to fall back on "formulaic imitation" and to experience uncertainty (195).

Because few chemistry students seemed to recognize the genres of either the questions or the answers, most did not use them in analyzing questions or planning answers. As first-year students, the chemistry writers attempted to map their high school schemata, roles, and habitual task representations (as source analogs) onto new college situations, as others have observed students doing elsewhere (Rosebery et al.; Bartholomae). In high school the students had been encouraged to rely on teachers' instructions and conform, rather than to learn how to reindex old knowledge and create new knowledge.

In his introduction to *Composing Social Identity in Written Language*, Rubin (9) emphasizes how instructors oversimplify the challenges students face and how, in comparison to oral discourse, written identity in college involves different conventions, organizational patterns, syntax, vocabulary, and other factors. For example, scientists often embed their logical propositions within independent clauses that emphasize communal performance: "**We see** A . . . . **We take** B to be C. . . . **So it is obvious** that Z." The chemistry students tried to imitate this distinctive pronoun use and syntax from the written cases and the classroom in the production of their written identity; they did not, however, usually understand the logical structure these pronouns and logical connectives were intended to introduce and they sometimes did not produce logical conclusions, as will be shown later.

Case-based theory, as an addition to mapping theory and constraint theory, was useful in uncovering problems in indexing, mapping, and reindexing material, as shown in the following section, because the test questions required students to apply concepts. Furthermore case-based learning is essential for problem solving and taking on adult roles. When combined with ideas about task representation and construction of purpose, the fundamentals of case-based reasoning, mapping theory, and constraint theory can help us understand several strengths and weaknesses in the writers' processes we observed.

Differences between successful and unsuccessful writing processes

After analyzing protocols and students' written exams, we concluded that an ideal student's test-taking processes would include analyzing test questions, efficiently searching memories, planning answers before writing, revising answers based on self-evaluation, and reasoning. Furthermore, an ideal student would accept the responsibility to organize answers logically and clearly for a fellow student; that is he or she would adopt a "teaching" role. Few students matched little Aaron's shift to the appropriate role. These processes occurred more frequently, however, when students wrote their answers in full paragraphs. Because the constraints of time, unreconciled concepts, and poorly indexed memory affected the writing and reasoning processes of students who received the highest scores, none of them fully reached this ideal.

A model answer (though not ideal) is Student 18's response to question 1a (see Appendix) in which the student adopts the appropriate "teaching" role, conducts an effective memory search, and reasons deductively (plain text indicates speech; italics indicates writing):

> Because it takes some certain minimum frequency to eject electrons, and this ejection can't be accomplished by just raising the intensity, it must be that radiation isn't a continuous stream; rather it's quantized into little packets of radiation. And since the energy of the ejected electron increases with frequency, frequency must be the measure of the energy in each packet.
>
> *In other words, once frequency and thus energy of each packet ("photon") is high enough, it supplies enough energy to remove the electron from the metal. Any frequency above the threshold frequency supplies an excess of energy to each electron, measured by each electron's kinetic energy*.

Students who write successful answers are able to select the most appropriate or useful elements from the cluster of meanings associated with a particular term. The students recognize which definition, example, or model applies in a given set of circumstances, and can decide when to eliminate less useful concepts. In the example above, Student 18 immediately rules out the possibility that intensity is the factor critical to explaining the photoelectric effect and correctly focuses instead on frequency.

A good answer, which would be useful in teaching someone, not only defines terms carefully, but also demonstrates an understanding of the relationship between experimental observations and theories. An answer based on deductive reasoning presents important premises and deductions in a logical, sequential order, is well organized, and contains cues that signal logical relationships between ideas. Notice above how Student 18's response to question 1a presents a logical progression from the given observations to conclusions. He includes transitions and rhetorical cues like "because," "it must be that," and "since" to express the relationship between his reasons and conclusions.

Successful exam writers also recognize when a word is used with different implications in various models or theories (as "valence" or "electron" is, for instance, in Lewis models and in atomic shell theory). Recognizing when an explanation is not adequate is vital in paradigm-changing and solving problems that no longer can be addressed by traditional practices of "normal science." For students to experience the challenge of historical discoveries (or to address ill defined problems in the future), they must also experience the frustration of vocabularies and concepts that do not accomplish their purposes.

Student 14, a good but frustrated student, illustrates the practice of determining what tasks a question requires: "I guess I don't quite understand—(reads) "in terms of the nature of radiation," I'm assuming that's in terms of—they want us to talk about the particular nature of light." This student can also handle seeming dissonances between presented facts and memorized facts by looking for dissonances and writing about them according to the genre conventions of exam writing. Student 14's almost-perfect response to question 2a (see Appendix), for example, treats the question as a "compare and contrast" question, as her use of transitions such as "when," "however," and "in this case" suggest (plain text indicates speech; italics indicates writing):

> *We must first understand that valence is applied when atoms combine with another molecule. Affinity, however, refers to the energy released when an electron is added to an atom. This atom does not combine with others in this case. We see the oxygen atom alone is a stable atom with no net charge. We also note that its valence shell can accommodate two more electrons. When taking on an extra first electron, oxygen will release a bit of energy, which is resulting in a positive electron affinity value. However, the affinity for a second electron is negative, because we already have a negative ion, O-. Therefore, there is no reason why it would want to be more charged. The valence of an oxygen atom, however, is two in this case, because valence refers to the*

> *sharing of electrons. When electrons are shared, they do not take on the full negative charge as if oxygen were—as when whole electrons are simply added to a lone O. Therefore both spaces left in the valence shell of an O- can be filled.*

Here, Student 14 answers the question by comparing and contrasting two hypothetical situations, that of an oxygen atom taking on a first electron and that of one taking on a second, a logical and rhetorical strategy appropriate to the question type. However, the answer is only near-perfect because the student falls back into the metaphoric discourse of Lewis structure models (in which atoms "want" or do not want events to happen) instead of explaining the influence of effective nuclear charge on electron affinity.

Successful exam writers demonstrated an awareness of when they were not correctly approaching a question. For example, after reading question 1a, Student 21 responded:

> *Since, when they increase the frequency of light above the threshold, the only resultant change in outcome*—that's a little bit redundant, but whatever — *is that the kinetic energy of the electron increases. We can then conclude that an increase in frequency increases the energy of light.*
>
> Now, I just realized that I haven't exactly answered the question. What he asked me to do was to explain how we can account for these observations in terms of already knowing the nature of radiation. He didn't ask me to deduce the nature of radiation from the fact that we make these observations.

Although we have not included Student 21's planning phase above, this student planned his answer carefully, and more importantly, he paid attention to what the question actually asked, as his realization that he hasn't "exactly answered the question" indicates. This recognition could, of course, be imagined as a teacher's concern for responding to a student's question, but nothing else in the student's protocol indicated that he was doing anything but complying with the exact terms of the instructor's question to him.

Not responding to their own perceptions of dissonance separated unsuccessful test-takers from successful ones. Question 2a asked them to explain, "in terms of the properties and energies of the occupied orbitals in the valence shell of the given atom," why it is true that "the electron affinity of oxygen for a single electron is positive" despite its being negative for a second electron. Student 1 read this question and simply said, "Why would it be negative for the second electron?" and immediately moved on to 2b. Granted, this is too brief a comment to indicate precisely what the student was thinking; however, this response—"Why would it be?"—*was* the question. That the student made no effort to explore his own paraphrasing of the question suggests that he was unable to differentiate between the question's fundamental problem and his own uncertainty.

Student 2 had similar difficulties coming to terms with this question:

> (planning). . . Maybe it has something to do with the fact that—hmm—this is odd. Electron affinity means it wants to attract another electron. Well, it already has 2P, and it's going to make another pi and the last one—I don't see why there wouldn't be an affinity for it. For a single electron, it's positive, but for a second electron, it's negative. I know—that's kind of strange. I'm going to explain the second one, because I can do it.
>
> *(writes) The valence of oxygen is two because there are two spaces in the 2P bonding orbital.*
>
> (planning) Affinity means want. It doesn't require any extra energy to put those electrons into—okay, let's talk about this. Oxygen is usually a double molecule, so usually it only wants—well, if it had seven electrons, it could still bond to something else. At the same time, I don't understand why it wouldn't want eight. I could see the fact that electrons repulse each other. When you put something into its 2P orbital, you kind of have problems, because there are more electrons there, and it creates a lot of repulsion. But—I don't know.

Student 2 wrote only the single italicized sentence as an answer. He came closer to a correct answer *after* writing this one line with his recognition that repulsion is involved, but, for whatever reason, he quit writing. Instead, he played it safe by answering the part he definitely knew, an error that suggests that, like Student 1, he did not distinguish between the question and his own uncertainty—the question asked him to resolve an apparent tension between two facts, and just commenting on one of those facts was to disregard the question. A desire for coherence seems to have caused him to abandon the attempt to explain the question's dissonances.

In addition to experiencing intense need for coherence and time pressures, the students had the most trouble with information retrieval, according to our protocol analysis. Most students tried to use the vocabulary of formal logic and the conventions that they associated with scientific discourse (for example, "we know that"), as Student 2 did when answering question 1b:

> Okay, well, *we know that* you can predict the frequencies. *What do I know*? *I know that* only specific frequencies are emitted because you only have certain energy levels, ...

Student 6 likewise used the structure of formal logic as a memory probe when answering question 2c:

> . . . *In the period, as we have more electrons* . . . electrons . . . the atoms . . . no, when there's more electrons, *they are attracted*, attracted *more to* them, to *the nuclei, decreasing the energy.* Therefore, what? Yeah. *Therefore, the radii decreases also*. . . .

Student 6's response illustrates how students started writing not just without planning, but without necessarily knowing where their logic would lead them.

Using formal logic as a heuristic helped students recall the facts on which a correct deduction depended; however, difficulties occurred when students used the same stock phrases both as heuristics during prewriting and as transitions in their finished answers. Most students' exam writing lacked a distinct prewriting phase; they generated and shaped their answers simultaneously. Consequently, the transitions that should have made their logic clear seemed instead to have been thrown in inexplicably.

Student 19's first spoken response to the Question 1a (Appendix), for example, has the form of a deduction, but clearly the second half of her sentence does not logically follow from the first: "First of all, radiation is a type of wave, so frequency, wavelength, and amplitude are all properties of waves." This student was not making logical connections; rather, she was only retrieving what she had stored in memory.

Appropriate connections were more likely to be established when students wrote their answers in full paragraphs. Although most students wrote their answers in the form of paragraphs, some sketched only brief list-like answers that resembled class notes more than the type of writing we are accustomed to seeing on essay exams. When we asked Hutchinson whether he felt such differences generally corresponded to the quality or correctness of an answer, he responded that he does not prescribe to his students the form in which they should write their answers but tells them only that as long as an answer presents the necessary information in a logical order, it receives full credit. Despite his sense that such formal matters were not among the criteria for evaluating answers, when we looked at actual exams, we discovered that the highly scored answers were, without exception, among those written in the form of complete paragraphs. Students 1, 3, and 4 wrote list-like answers consistently throughout the test and did poorly.

This observation indicates, admittedly, perhaps nothing more than that students uncomfortable with the material the test covers are simply unable to write coherent paragraphs; nevertheless it is possible that the act of writing complete sentences and paragraphs encourages students to reproduce not merely the facts their textbooks supply, but to look for the logical connections between the facts they recall, and more importantly, to plan their answers at least partly before actually writing. When Student 1 encountered the first test, he fell back on a familiar strategy: "The first test was hard, since I didn't even know how to answer the questions. I tried to answer them like essay questions, but I realized it was better to answer them as an outline, just as I summarized the case studies. . . ." In this instance, the student had reduced the task representation to a simpler instruction, one he had followed in test preparation. This student's inferences about how to present his answers were, in fact, wrong.

Conclusion

As Winsor's longitudinal study of four engineering students demonstrated, students in science courses seldom are taught about the rhetorical side of their discipline. Their courses focus on calculation, formulae, and physical properties, not the way that issues are formulated in language. The oddity of essay questions on a chemistry exam reveals just how much the rhetorical dimension of chemistry—not just engineering—is usually repressed. Successful and unsuccessful chemistry writers differed in their awareness of the genres of questions, ability to search memory, judgment in relating key terms to appropriate models or concepts, understanding of logic, use of planning, application of rhetorical knowledge, and adoption of appropriate roles.

We conclude that students' test taking schemata generally suited traditional tests requiring recall rather than the knowledge creation Hutchinson asks for. In the typical test-taking scheme, the four cognitive processes of composing (planning, elaborating, structuring, and monitoring) are drastically modified. Continuing to use this typical test-taking scheme undermined students' efforts to deal with Hutchinson's exams. Simple recall is an inadequate substitute for analogical reasoning on exams which, as Student 1 commented earlier, ask questions that "don't directly apply to the cases in the book." The three question types on Hutchinson's exams ask for the kinds of exploratory and constructive processes usually associated with heuristics for planning papers and the elaborative processes better explained with concepts from analogical reasoning theories. The traditional test-taking scheme is consistent with the students' awareness of their roles as people being interrogated. To assume that simply telling students to "become instructors" will cause such a transformation is naive. In general, chemistry instructors (whether Coppola and Daniels (77) or our own faculty) seem not to recognize the complex nature of "becoming a teacher" in discourse.

Concepts of indexing, mapping, and role assignment from psychological theories of analogical reasoning can help identify students' difficulties and instructors' opportunities to improve student learning. These concepts extend models of cognitive processes used in earlier studies of "reading to write" in ways that help identify students' problems and differences in processes.

Recommendations

Improve indexing through in-class writing, journals, and the World Wide Web

How can students be helped both to retrieve the facts they have learned from reading case studies and to recognize their applicability to new contexts? In successful case-based courses, Kolodner finds that "built into the curriculum is the reflection needed to promote analysis and encoding of students' experiences in ways that will make them useful and accessible in the future at opportune times" (58). We believe, therefore, that it is essential that students be given more opportunities for such reflection and be required to write outlines of cases. We recommend (1) helping students index their understanding of cases through outlining, journals, in-class writing, and on-line discussions, (2) making test writing a course topic by calling attention to question types and providing annotated examples of good and bad answers, and (3) revising the wording of questions to provide strategic cues.

In their pretest interviews, many of the students reported favorably on the benefits of having followed Hutchinson's advice to write outlines and answers to sample questions. Student 2, for instance, claimed that he wrote out answers to all of the study questions because "It seems to me that when I write things down, as opposed to hearing about them or seeing them, I remember them ten times better." Student 14 agreed, "I think there were times where I thought about them [the sample tests] more and just didn't write as much as I usually do, and I find myself doing not as well on the exams in general, in this and other classes."

The tests invite students to recognize the relevance of covered material to new contexts, but as Kolodner argues, students will seldom recognize such connections if they have not already spent time "reflecting on what they have learned and when they might find those lessons relevant in the future" (58). Students could improve their indexing through in-class writing, perhaps summarizing the logical steps in the case problem they had just solved in class discussion, or at the end of class students could write for a few minutes about what they have just learned. They could also practice in class the kind of writing required on exams; for example, they could describe the experimental evidence that supports a known theory or try to develop a theory using the evidence just discussed in class. Such practice would help students make those sorts of connections when taking exams. Also beneficial would be responding to the case studies in a journal or doing more speculative forms of writing.

Currently, Hutchinson assigns his students to optional study groups led by graduate assistants; many choose not to attend these group meetings. Those students who failed to attend study groups missed the experience of collaboration Schleifer notes as customary in the sciences: activities in which the roles of master and apprentice are exchanged as scientists develop disciplinary expertise (446-447). These study groups might become even more productive if students and their teaching assistants discussed problems together in person, in on-line discussions, or in chat rooms on the World Wide Web. Instead of simply reading old tests posted on a web site, students might respond to such tests in writing if they knew that a teaching assistant or even a fellow student would send back corrections and comments. The more students write about chemistry before being tested on their ability to do so, the less difficulty they should have in test situations.

Editing sample answers, practicing logical connections and taking mock tests

It is possible that the act of writing complete sentences and paragraphs encourages students to reproduce not merely the facts their textbooks supply, but to look for the logical connections between the facts they recall, and more importantly, to plan their answers at least partly before actually writing. Because the more polished a student's writing is, the higher the score answers receive, students should be required to write their answers in paragraphs and the course should give them opportunities to develop their ability to do so. Such opportunities might include learning how to analyze questions, studying bad answers as well as good ones, editing incomplete answers, and taking mock exams in "real test" environments.

Students must learn to recognize the different types of examination questions and answers. Making question analysis demonstrations a topic in class lectures might enable students to understand the subtleties of exam questions. Such demonstrations might include how to identify key words and phrases ("explain in terms of" is one of Hutchinson's favorites) as well as differences in argument structure. Students could be given a list of facts needed in a sample answer and asked to revise these snippets into polished answers with strong logical connections. Such practice will help students index features of good answers and useful writing tactics.

Additionally, students would likely perform better on exams if they were given class time to take a mock exam before taking each regular one—or at least before the first one. Failure in a practice situation can be more productive than penalizing students with a low first exam grade. Failure can promote learning, since, as Kolodner points out, "Failure at applying an old case in a new situation . . . might result in reinterpreting (reindexing) old situations or discovering new kind of interpretations (indexes)" (61). But to learn from their failures in this way, students need to spend time reinterpreting the case studies. It seems reasonable to assume students are more likely to reflect on their failures while they are still studying than after they have been disappointed by a grade that counts. Few students write new answers to graded exams—more often, they just vow to do better next time. Hutchinson relies on the first exam to provide students with their first negative experience (Interview). This practice might be counterproductive; students who initially try writing the practice answers and outlines might cease doing so, deciding that these study methods are not effective.

Question wording

Finally, instructors should experiment with different ways of wording questions. For instance, Question 1a tells students to "explain briefly how we can account for these observations in terms of the nature of radiation." The doubled instruction to explain how we explain might confuse students. Simplifying this command to "Explain these observations in terms of the nature of radiation" might clarify that students are to explain the observations themselves. Similarly, because some students mistake the apparent contradictions in the pairs of observations' (Question 2 a-d) for their own lack of understanding, they should be warned explicitly—at least on the first exam—that they need to resolve apparent contradictions. Since question types are repeated, the tests might also include general directions relating to particular question types.

If implemented, these various recommendations would give a greater prominence to the rhetorical dimension of chemistry. They would also help students become more aware of their learning processes and their roles in test situations, an awareness that would be valuable in many other courses. In the long run, students would be better able to apply their problem solving skills to reasoning about chemistry and about other topics in the 21st century's turbulent environment.

Appendix: Practice Test for Chemistry 101 Questions 1 and 2

1. (a) The photoelectric effect refers to the observed ejection of electrons from the surface of a metal exposed to radiation. It is found that (i) no electrons are ejected unless the light has a frequency as least as

great as a certain minimum “threshold” frequency; and (ii) the kinetic energy of the ejected electrons increases proportionally with the frequency of the light above the threshold frequency. Explain briefly how we can account for these observations in terms of the nature of radiation.

(b) The spectrum of radiation emitted by hot hydrogen atoms consists of radiation with specific frequencies n given by the Rydberg formula:

$$\nu = R\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

where n and m are integers with m > n. Give a brief argument for the existence of quantum energy levels for the electron in a hydrogen atom based on the Rydberg formula combined with your explanation of the photoelectric effect.

2. Explain each of the following observations in terms of the properties and energies of the occupied orbitals in the valence shell of the given atom. (There are two observations in each part; explain both of them.)

(a) The electron affinity of oxygen for a single electron is positive, but for a second electron is negative. Nevertheless, the valence of an oxygen atom is two.

(b) The ionization energy of a potassium atom is less than that of a calcium atom, whereas the ionization energy of a potassium ion, K^+, is larger than the ionization energy of a calcium ion, Ca^+.

(c) Within a group, the atomic radii always increase with increasing atomic number, but within a period, the atomic radii always decrease with increasing atomic number.

(d) An inert gas atom has a low electron affinity but is strongly electronegative. NOTE: Begin your answer by defining in chemical terms what we mean by electronegativity.

Works Cited

Bartholomae, David. “Inventing the University.” *When a Writer Can’t Write: Research on Writer’s Block and Other Writing Process Problems.* Ed. Mike Rose. New York: Guilford, 1985. 134-65.

Bazerman, C. *Shaping written knowledge: The genre and activity of the experimental article in science*. Madison, WI: University of Wisconsin Press, 1988.

Berkenkotter, Carol, and Thomas N. Huckin. *Genre Knowledge in Disciplinary Communication: Cognition/Culture/Power.* Hillsdale: Lawrence Erlbaum, 1995.

Carey, Linda, et al. *Differences in Writers’ Initial Task Representations.*

Center for the Study of Writing Technical Report No. 35. Berkeley: U of California; Pittsburgh: Carnegie-Mellon, July, 1989.

Coppola, Brian, and Douglas Daniels. "The Role of Written and Verbal Expression in Improving Communication Skills for Students in an Undergraduate Chemistry Program." *Language and Learning Across the Disciplines.* 1.3 (1996): 67- 86.

Dias, Patrick. "Initiating Students into the Genres of Discipline-Based Reading and Writing." *Learning and Teaching Genre*. Eds. Aviva Freedman and Peter Medway. Portsmouth: Boynton/Cook, 1994. 193-206.

Flower, Linda. *Studying Cognition in Context: Introduction to the Study*. Center for the Study of Writing Technical Report No. 21. (Reading to Write Report No. 1.) Berkeley: U of California; Pittsburgh: Carnegie-Mellon, May, 1989.

Flower, Linda. *The Construction of Negotiated Meaning: A Social Cognitive Theory of Writing*. Carbondale: Southern Illinois UP, 1994.

Flower, Linda, and John R. Hayes. "A Cognitive Process Theory of Writing." *College Composition and Communication* 32 (1981): 365-387.

Gentner, Dedre, and Keith Holyoak. "Reasoning and Learning by Analogy." *American Psychologist* 52.1 (1997): 32-34.

Gentner, Dedre, and Arthur Markman. "Structure Mapping in Analogy and Similarity." *American Psychologist* 52.1(1997): 45-56.

Graders of Chemistry Exams. (Kelly Ann Gillogly, Sue Wiediger, Thomas Thrash) Interview. 24 Jan. 1997. Houston, TX.

Holme, T. A. "Using the Socratic Method in Large Lecture Courses: Increasing Student Interest and Involvement by Forming an Instantaneous Group." *Journal of Chemical Education* 69(1992): 974-977.

Holyoak, Keith, and Paul Thagard. "The Analogical Mind." *American Psychologist* 52.1 (1997): 35-44.

Holyoak, Keith, and Paul Thagard. *Mental Leaps: Analogy in Creative Thought.* Cambridge: MIT Press, 1995.

Holyoak, Keith and Paul Thagard. "Analogical Mapping by Constraint Satisfaction." *Cognitive Science* 13 (1989): 295-355.

Hutchinson, John. *Case Studies in Chemistry.* 2nd ed. Boston: Houghton Mifflin, 1995.

Hutchinson, John. Interview. 24 Jan. 1997.

Kolodner, Janet. "Educational Implications of Analogy: A View from Case-Based Reasoning." *American Psychologist* 52.1(1997): 57-66.

Kuhn, Thomas. *The Structure of Scientific Revolutions*. 2nd ed. Chicago, IL: U of Chicago, 1970.

Miller, Carolyn R. "Genre as Social Action." *Quarterly Journal of Speech*. 70 (1984):157-78.

Nelson, Jennie. *'This was an easy assignment': Examining How Students Interpret Academic Writing Tasks*. Center for the Study of Writing Technical Report No. 43. Berkeley: U of California; Pittsburgh: Carnegie-Mellon, Oct., 1990.

Rosebery, Ann S., et al. *The Problem-Solving Processes of Writers and Readers*. Center for the Study of Writing Occasional Paper No. 7. Berkeley: U of California; Pittsburgh: Carnegie-Mellon, January, 1989.

Rubin, Donald, "Introduction: Composing Social Identity." *Composing Social Identity in Written Language*. Ed. Donald Rubin. Hillsdale: Lawrence Erlbaum, 1995. 1-30.

Schleifer, Ronald. "Disciplinarity and Collaboration in the Sciences and Humanities." *College English* 59.4 (1997): 438-452.

Stein, Victoria. *Exploring the Cognition of Reading-to-Write*. Center for the Study of Writing Technical Report No. 43. (Reading-to-Write Report No. 5.) Berkeley: U of California; Pittsburgh: Carnegie-Mellon, May, 1989.

Sturnick, Judith. "Looking at Change in Education." Third National Writing Across the Disciplines Conference. Charleston, SC. 7 Feb. 1997.

Winsor, Dorothy. *Writing Like an Engineer: A Rhetorical Education*. Mahwah, NJ: Lawrence Erlbaum, 1996.