

Examination of Technologies for Student-Generated Work in a Peer-Led, Peer-Review Instructional Environment

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Abstract -- There is a growing literature demonstrating the effectiveness of using computer environments to assist students' in visualizing science and mathematics concepts. However, with many of these computerized learning environments, students do not have the option of manipulating the environment. Instead, they are presented with pre-made visualizations. Enabling students to display their understanding through multiple representational forms is more interesting. In our peer-led, peer-review environment, students generate a complex, literature-based, multimedia text on which their final examination is based. However, there are great time and personnel costs in this design. Collaborating with SRI Inc., we are addressing these demands via the ChemSense Studio. This second-generation tool allows students to create texts, images and animations using one simple application. Peer-review is facilitated. We have begun to develop and modify methods of visual discourse analysis in order to examine the effectiveness of the ChemSense Studio in assisting students in their development of representational competence.

Index Terms—Education, Chemistry, Collaborative Work, Web Page Design.

I. OVERVIEW

“Structure and Reactivity” is the first-year chemistry course at The University of Michigan. Each Fall, 160 students in the 1200-student course earn Honors credit by participating in weekly 2-hour supplemental instruction sessions we call Structured Study Groups (SSGs). Students bring written assignments to the sessions and engage in structured peer group critiques facilitated by upper-level undergraduate leaders. Projects broaden and deepen the students' learning of associated course topics. In the second term, there is a separate section of the course where all of students are in SSGs. In these sessions, students represent their ideas in writing, orally, and through computational tools. Since 1996-97, one of the term-long projects requires all of the students contribute to the construction of a written and HTML literature-driven resource. Creating animations of reaction mechanisms and interactive correlation of spectroscopic assignments causes students to consider the subject matter in ways more aligned with an instructor's work. Ultimately, the multimedia text (print, CD, and web site) is fully owned by the students, and they must seek out each other's expertise in order to examine their understanding. The final examination

in the course is based completely on the student-generated text (see: <http://www.umich.edu/~chemh215>).

Overall, students are being asked to provide higher level explanations than they might typically be asked to do in a course. Consequently, they should also develop higher levels of understanding. Because they are using a variety of representational tools, they should also develop higher levels of representational competence as a result from needing to provide these sorts of explanations. The representational forms that are used for structural chemistry, especially with organic compounds, should encourage an increased understanding along five dimensions through which structural information are typically represented in pictorial form. For chemical reactions, these are changes in connectivity, geometry or shape, concentration, aggregation, and state.

In collaboration with the Center for Technology in Learning group at SRI International, ChemSense Studio was designed to reinforce the principles of collaborative learning and representational variation established in the Honors sections of the second semester Structure and Reactivity course. In principle, this tool will enable large numbers of students to benefit from making the kinds of rich explanations that is significantly harder to scale up without coding the instructional methodology into the computational tool. We have conducted two implementations of ChemSense Studio in the first semester of the course. In Fall, 2000, a group of students in the first-semester SSGs implemented a single, integrated lab and lecture ChemSense Studio activity that complemented the existing SSG curriculum. In Fall, 2001, 3 of the 8 SSG sections used ChemSense Studio throughout the entire semester; all of the work was constructed and reviewed in the electronic environment, the sessions were held in a computer-based classroom, and the written curriculum materials were used in exactly the same form in the ChemSense and non-ChemSense sections. Data were obtained during the fall 2002 semester from approximately 150 students in the Chemistry 210 Structured Study Groups. Students were evenly divided and randomly placed into groups that did all of their work in ChemSense or that did their work in traditional pen (or printer) and paper. There are two data sources: student work and quizzes. All of the student work from the students in the ChemSense groups is preserved, while representative work from the traditional groups was collected. Both groups received either paper quizzes or ChemSense quizzes. A paper pretest was given to both groups, then 2 quizzes during the semester, and finally a paper posttest to both groups. The pre/posttests and quizzes included questions that were

answered graphically as well some that were answered in written sentences.

II. INTRODUCTION

For all that has been written and said about assessment methods, we think it is useful for instructors to realize that we ask our students to teach us on our examinations [1]. In all cases, whether an exam is in written or oral format, an instructor takes on the student role as questioner and learner, while the student is the one who provides explanations. Yet concrete, explicit opportunities for students to build the skills for this role-reversal are rarely provided. Writing a report, giving a presentation, and taking exams are all capable of doing this job, in principle, yet in practice students spend much time delivering answers. Faculty members end up as judges who determine what is wrong and what is correct. By pointing out to students that during examinations they are assuming the teacher's role, it allows them to confront the need to learn how to express their understanding before the inevitable examination. In order to emphasize the role that teaching, as well as preparing to teach, can have in the learning process, we have actively promoted ways for students to practice their teaching skills before the examination. These ideas are strongly aligned with the principles of reciprocal teaching [2-5], and especially with work on the power of explanatory knowledge [6-9].

The implications from the research on explanatory knowledge are profound. Learning environments need to include structured opportunities for students to reflect on their learning in ways that specifically develop their interpersonal communication skills, understanding that by doing so they can develop explanatory knowledge. Although it is generally overlooked, explanatory knowledge is an important outcome from group learning activities where students must discuss the basis for their answers, conclusions and developing ideas [10].

Critical listening and formative critique are important skills that accompany explanatory knowledge because communication is a two-way street. Effective teaching (explanation) means looking at a student's work (listening) in greater depth than simply taking an inventory of 'correct' and 'incorrect'. An effective teacher can look at a student's work from the student's perspective as well as his or her own, thereby using an expert, or just an outside perspective to analyze the kinds of assumptions that could lead to the observed errors. The intellectual challenge that arises from this viewpoint is thinking about how to reconcile inconsistencies between student and teacher perspectives, and also how to construct a bridge between them that requires effort from both directions. Creating multiple modes for expression (written, verbal, pictorial, etc.) improves communication between parties because it provides cross checking (or "triangulation") of ideas [11-12].

Faculty colleagues in disciplines that more openly acknowledge their reliance on developing skills for expression (literature, art, dance, theater) all rely on the performance studio in their instructional design. The studio is a place where the desired skills can be displayed to a peer group of learners, usually under the guidance of a more experienced individual who critiques as well as organizes peer review, and

generally after some amount of solitary preparation has occurred outside of the studio (wrote a story, filled a canvas, or learned the lines). A great deal of high-value learning takes place in the studio because every participant has done something about a common task (write a story, fill a canvas, or learned the lines) that carries the results of their individual efforts. We have asked two questions: (1) Where is the comparable "performance studio" for chemistry learners? And (2) What modes (or mediators) of expression are best-suited for learning in chemistry? Laboratory activities, and documenting and reporting results, should fulfill this role, but there are many reasons why this is not true in practice. Many introductory laboratories can be performed without processing the ideas. In any event, regardless of the design of laboratory courses, skill-building with those activities would be too far from the expected mode of expression on an examination.

This paper begins with an instructional design for supplemental instruction that draws from the ideas presented above. The discussion then moves on to how student-generative work has been used to support student learning. Technology plays an important role for the group work, from simple, commercially available representational tools, to more complex interplay between student learning and task design to produce new and more authentic opportunities for students to represent their understanding. This program has been limited to a relatively small (100-150 student) and self-selected population during its development. Because the program is also resource-intensive and demanding on student time, it is not amenable to an easy scale-up. ChemSense Studio is designed to facilitate the implementation of this program into larger and less well-supported instructional settings. We end with the results from three pilot implementations of ChemSense Studio into a first-year college chemistry course.

III. STRUCTURED STUDY GROUPS I.

Peer-group learning and representational tools

In our Structured Study Group (SSG) program, a cohort of 120-160 first-year Honors students from a standard 1200-student course, earn their Honors credit by participating in extra weekly 2-hour sessions that are shaped, metaphorically, along the lines of a "performance studio" in the Arts [13-16]. Assignments, in the form of common (not identical!) tasks, are subjected to peer presentation and peer critique facilitated by upper-level undergraduate leaders. Although both productive and engaging, we designed SSG tasks to go beyond only directing students to work in groups or only providing them with problem sets. Students in the Structured Study Groups follow a detailed curriculum that helps them to develop the kind of explanation skills that we believe are attached to a deep mastery of the subject matter.

During each session, the meeting time is typically divided between a number of activities. Each participant brings a duplicate set of his or her written assignment from the previous week. These assignments generally involve the creation of examples within a given context. In the very first assignment, they pick a C₁₀-C₁₃ molecule from a chemistry journal (after learning, in their session, how to decode line

formulas, what journals are, where they are found, and what proper citation format looks like) and are directed to construct 5 rational examples of molecules with the same formula. They then propose rankings for their created molecules based on 3 of 6 properties, including, for example, magnitude of dipole moment, boiling point, and solubility. They must also include written descriptions of their rationales. Later, a typical assignment might be to find an example of an S_N2 reaction in a chemistry journal and format it as a quiz problem appropriate to the level of the class. The students are always directed to provide a brief statement that puts the reaction in context, a copy of the journal pages from which the example is derived, and a properly formatted citation. At the beginning of the session, the students submit one copy of their work to their leader, and the other copies are redistributed to the class. One or two rounds of peer review follow. The reviewer does not correct the other student's paper, but rather answers a set of factual questions about the other's work: Does the molecule or reaction fit the prescribed criteria (yes or no?); is the format and information appropriate to the level of the class (yes or no?); is the citation formatted correctly (yes or no?). During this time, the discussion within the group is free-wheeling, and it is the time of greatest learning for the students. Although the only duty is to mark off a "yes" or "no," the first round of peer review can take up to an hour. Only when faced with reviewing the work of another, can the student deal with issues that were either incorrectly understood or that simply did not occur to them. The discussion that proceeds from the peer review process requires the reviewer to conceptualize and express ideas from a colleague's work that can conflict with his or her original work because there are errors in one or the other. In addition to developing explanatory knowledge, SSG students have a structured opportunity to make, recognize, and correct their errors before they get to an examination. After the review process is completed, the reviews and the unmarked papers are returned to the originator, and he or she has a chance to decide if any corrections are needed. This second set of assignments and the reviews are collected, and they form part of the basis for the leader's evaluation of the student's performance that day.

Strands of advanced topics also comprise part of the class period. For example, in the first term, part of four or five class periods are devoted to discussion and in-class exercises involving Frontier Molecular Orbital theory. In the second term, spectroscopy, bioorganic chemistry, and more FMO-related work (electrocyclic, sigmatropic and cycloaddition chemistry) are alternatively introduced over the course of the meetings. Finally, the next week's assignment is presented, along with any supporting discussion, examples, or software (ChemDraw, Chem3D, and molecular modeling packages such as CAChe or Spartan) training needed to clarify the expectations. One of the overarching goals is for students to develop the ability to create meaning from new and unfamiliar chemical information, generally from the primary literature. In order to represent their understanding to others, we require them to use the kinds of representational software used by professional chemists.

The Honors students are graded for their participation in the weekly groups within the context of the larger 1200 student

course. Every week during the term, the seven student leaders and a faculty member meet to discuss the upcoming and previous assignments, the grading criteria, and the classroom challenges faced by the leaders themselves. The leaders are then responsible for assigning each student a grade based on a U (unsatisfactory), S (satisfactory), O (outstanding) scale. In electing to participate in the Honors groups, students agree to have their course grades based on a two-part scheme. First, the entire class of Honors and non-Honors students have their grades determined as usual, based on their four examinations. In order for an Honors student to maintain this grade with an "H" designation, he or she needs to have achieved an "S" average or greater from their group leader, with an "O" counterbalancing a "U." A less than "S" average results in a proportional reduction of the student's grade, with an all "U" average reduces the student's course point total by 10% along with whatever grade change might accompany that reduction.

IV. STRUCTURED STUDY GROUPS II.

Second semester: Using higher technology

During the second term of *Structure and Reactivity*, students have the option of enrolling in what is advertised as a "project-oriented" section of the course. This section of 65-100 students is isolated from the rest of the 800-student course, with a single faculty instructor supervising the lecture and laboratory courses in addition to the SSGs, which are required for all of the students in this section. There are two layers of SSG assignments. The first is a series of weekly tasks that are comparable to those in the first term course. Projects involving various technological environments comprise the second layer of assignments. One of these projects is described here.

A. The HTML-Manuscripts Project

In addition to technical accuracy, representational competence in chemistry requires students to make decisions about how different kinds of representations are better matched with what needs to be expressed [17-19]. Some of the relevant instructional goals for the second term course are for students:

- (1) to more fully appreciate the molecular dynamic change in chemical reactions
- (2) to learn how to correlate graphic and tabular spectroscopic data with molecular structure
- (3) to increase confidence in assigning meaning from reading primary writing (journals)
- (4) to promote multi-representational modes of communication with decision-making

The class is naturally subdivided into SSG sections of 15-18 students. Within each SSG, subgroups (or "smaller study groups," ssg) of 3-4 students are created. Each SSG takes ownership of a journal article selected by the faculty instructor for the appropriateness of its content to the general subject matter of the course. During the first SSG meetings of the term, students receive the following instructions:

"During the term, you will have a variety of SSG assignments based on these articles. Your SSG will need to

subdivide into a set of six, three-person *smaller study groups* (ssg). Each ssg will be responsible for three specific tasks. Let us take paper No. 1 as an example (Hunt, J. A.; Roush, W. R. *J. Org. Chem.* 1997, 62, 1112-1124.), SSG 1 is made up of 6 ssgs, 1.1 – 1.6.

"After using written and oral presentations within your SSGs for each of the items listed below, you will construct a web site that integrates the hypertext versions of all of the following into a single document for your entire class (the assembly of ssgs into the SSGs, and the SSGs into the class). Both web and print versions will be required. You will also have the opportunity to burn an archival copy of the web site on a CD-ROM disk."

(1) Describing, in a brief paragraph, the chemistry of your step.

- What kinds of reactions are taking place?
- What is the overall change? What precedents are there for the change?
- What kinds of interesting selectivities or other features were part of your transformation?
- Each SSG has a few trigger questions about some of the chemistry represented in their step.

(2) Creating an animation for the mechanism of the transformation(s).

(3) Creating a correlation between:

- the proton NMR spectrum of the product and its structure (click or mouseover an absorption signal indicates the hydrogen atom group, and *vice versa*)
- the carbon NMR spectrum of the product and its structure (click or mouseover an absorption signal indicates the carbon atom group, and *vice versa*)
- the text of the experimental section that described the preparation of the product in your sequence and any terms, procedures or apparatus that are unfamiliar to you and/or your Chem 215H class in general (the experimental section should be carefully re-typed in HTML and, perhaps using side-by-side frames, deliver an elaboration and/or illustration and/or picture of the term, procedure and/or apparatus).

In order for the students to accomplish the goals of this project, they need to master and combine a number of pieces of software, namely, ChemDraw (to represent molecules in 2D line formulas), Chem3D (to create 2.5D or stereoscopic images), CAChe (to create computationally valid molecular structural drawings), Photoshop or other appropriate graphics program (to manipulate the images), GifBuilder (to combine images into animations), in addition to whatever Java and HTML templates might be used by individuals. The SSG Leaders, who are junior and senior students getting experience in curriculum design and implementation, create and collaborate on the various lessons that are required to improve the technological literacy of inexperienced first-year chemistry students (see: CSIE, Chemical Sciences at the Interface of Education; www.umich.edu/~csie). The timeline for developing the complete HTML project involves parallel lessons, where students are learning the required software in preliminary tasks at the same time that they are mastering the subject matter demands of the assignment. For the latter, the students within the ssgs are responsible for working through

the chemistry that they are assigned so that they can present their understanding, orally and in writing, to their SSG for review and feedback. The groups must also decide on every aspect of the design in how they are going to represent the work to each other (and the world) at the course web site.

B. Technology and the learning environment

The following series of question helps to define the relationship between the technology and the learning environment. How does the technology enable the construction and manipulation of representational artifacts in ways that support more effective collaborative learning? The two most sophisticated representational tasks are described below. These activities are not simply different ways of representing something that could be easily done without the technology. In fact, they can only be done more poorly without the computer. Not coincidentally, the two underlying ideas are traditionally difficult concepts in learning chemistry. In other words, the topics discussed here are proposed to be difficult for students to learn because they are so cognitively demanding. The technology allows students to build visualizations for ideas that could not otherwise be accomplished.

Chemical reactions are a series of molecular collisions coupled with bonding changes. Because generating animations is a time-consuming and, until recently, inconvenient task for instructors, this fundamental concept could only be imagined and described, but not easily illustrated on an *ad hoc* basis during introductory instruction. For example, the reaction that takes place when light-sensitive sunglasses change from colorless to colored is represented this way:

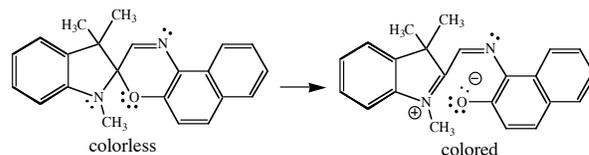


Fig. 1. Conventional (static) representation for a dynamic chemical process.

In order to represent a greater sense of change in static images, a curved arrow convention is used. While addition of these arrows is meaningful to a person who is literate in the meaning implied by this convention, it probably does not convey any more sense of motion and change than the first set of images.

Even the static images used to construct an animation does not convey the sense of motion, of course, that even a flip-book of these same images would convey (and still not as well as what animations can do because the interframe delay can be set for each image).

The animated version, if observed, matches the conception held by experienced chemists. As a number of students who have worked on the animation assignment have remarked: "We have never needed to think in such detail about a reaction mechanism as when we had to build a 120-frame version of it." Or, "I never appreciated before the sense of motion in bonding changes until we worked on the

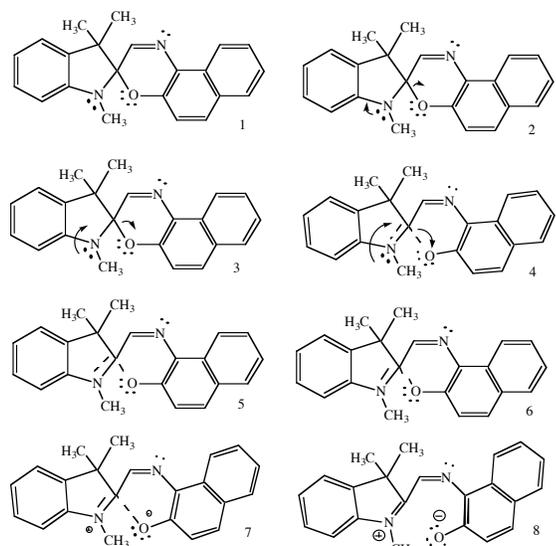


Fig. 2. Storyboard for a dynamic chemical process

animation project. It was really great to have the entire class's animations to study after all this."

There are four layers of collaborative work that building these animations interact with. First, the intimate association within the ssg group of 3-4 students: they must examine and work through each detail of each frame with each other, debating the chemistry and doing library work. Second, the ssg groups must think about presenting their thinking for their SSG, where another round of review occurs. Third, the SSGs aggregate as an entire course. The work becomes public and the members of the class then need to examine each other's pages. The fourth community involves an instructor! The aggregate work of the class would be literally impossible for an individual faculty member and even a small group of graduate students to create.

Why do they study the whole site at all? The site is a complex artifact of student work on sophisticated chemistry explanations. In order to provide more purpose than just another artifact of student learning, the site (and its print version) have significance to the course. From the start, the students know that the final examination in the course will be based on the student-generated text and hypertext. Furthermore, the instructor uses the student work to construct exam questions based on the inevitable, and expected, errors that will remain in the work. This method of testing has been a successful device for transmitting a two important lessons. First, that one should always have a critical eye when encountering test and hypertext. Second, that true ownership of one's education is possible, even if it means deconstructing one of the most central elements in a science course: the textbook.

Correlation of spectroscopic lines with structural elements in order to do molecular structural determination. The typical graphical output used to identify molecular structure is shown below, along with the structural conclusion made by a chemist.

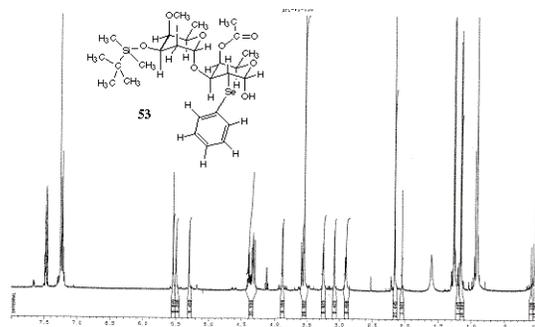


Fig. 3. Typical structural data and its interpretation.

One way to make the correlation is with arrows. Each line on the graph corresponds to each set of hydrogen (H) atom groups in the molecular structure. It is nearly impossible, with any clarity, to draw an arrow from each absorption peak to each hydrogen atom set. Just a few of these are shown in the next figure. While the correlation exercise can be done on the static, non-technological environment of paper and arrows, the results are not easily open to inquiry by others due to the complexity of the problem when all of the information is shown at once. On the other hand, these correlations are perfect candidates for mouse-over technology. Most students elect to use color-correlated relationships (two figures follow).

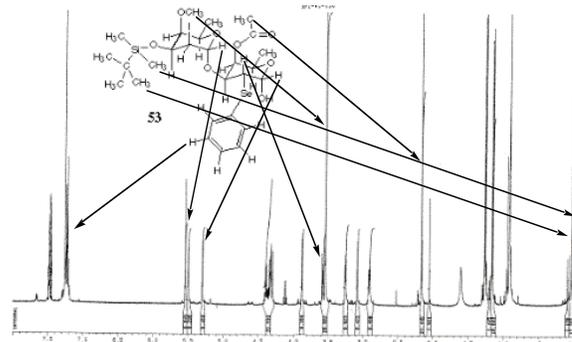


Fig. 4. Arrows are one mode of making correlation explicit.

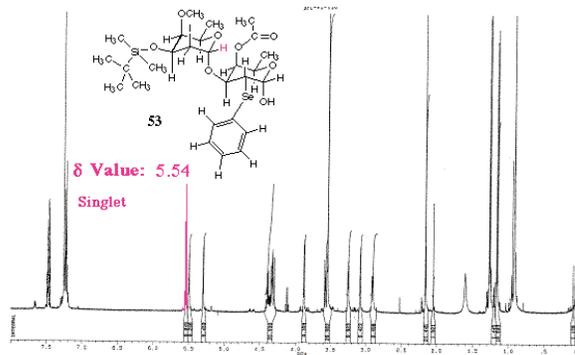


Fig. 5. Mouseovers are another mode of making correlation explicit.

There have been many different solutions to this representational problem posed by the students, many of which add a great deal of clarity to the issue of spectral correlation. Once again, the static image does not convey the interaction possible by being able to inquire by mouse-over on the peaks to relate absorptions to the structural elements, or vice versa by mouse-over on the structural elements to highlight the absorptions on the spectrum. Some students have elected to include textual explanations in dialog windows to further elaborate the connection when conducting the mouse-over.

Because the primary technology is only for generative purposes, it truly mediates the work of the groups. Creating the animations and the spectral correlations, and then on top of this the design of the site, the members of the small groups and the larger SSG groups must learn to negotiate the usual aspects of peer-based learning.

The nature of the curriculum and the tasks within the HTML project are clearly intimately intertwined with the introduction of technology into the course. A somewhat controversial aspect of the project has been giving the students freedom (and time) to think about page design issues. Chemist observers tend to want to focus on the subject matter issues and are less tolerant of a creative design. On the other hand, the design in which information is embedded is a relevant teaching issue. Only a few of the students react negatively to the demands of generating a sophisticated web site for a chemistry course because they are fully aware of the project when they sign up for the course.

This site, its accompanying text, and its use constitute an authentic form of student assessment. Indeed, there are many layers of assessment built into the project. One of them is peer-to-peer during the construction of the pages. The SSG leaders and the instructor provide another as the pages are examined. For all three years during their study for the final examination, these classes have spontaneously decided that they must meet as a class to rely on each other's expertise as the authors of the work. Well beyond an inquiry into our students' mastery of the chemistry subject matter, this project also allows the student leaders, through their monitoring of the group work, to assess questions like independence, reliability, and ownership, all of which figure into the evaluation component. These same qualities help identify the next generation of leaders.

V. CHEMSENSE STUDIO: EXPLANATORY AND REPRESENTATIONAL DIMENSIONS USED IN STRUCTURAL CHEMISTRY

A. *Figures and Tables*

There are five molecular-level themes (concepts) that are common instructional objectives for constructing chemistry explanations. These are connectivity, shape, state, aggregation, and concentration. Learning how to represent some of these dimensions (connectivity, shape) is typically done with static forms, although chemical reactions generally involve changes over time (i.e., dynamic process). The others (aggregation, state, concentration) are often expressed mathematically and depicted with static forms, but because

they rely on the dynamic action of multi-molecular systems, they are a difficult representational challenge.

These five dimensions are briefly described below.

Connectivity. The connectivity of atoms to make molecule structures sits at the core of contemporary chemistry. Chemical identity is expressed in terms of the molecular structure. Patterns of observations on many thousands of sophisticated chemical examples has led to one of the most important advances in chemistry: the structure-reactivity relationship. Chemical reactions, that is, the transformation of one set of compounds to another, are changes in chemical identity and are expressed in terms of connectivity changes. These patterns of connectivity are often associated with certain perceptual qualities of a compound.

Shape. Molecular structure involves more than connectivity; molecules also have shape. And chemical changes involve more than changes in connectivity. A complete understanding of chemical reactivity also involves understanding the changes in spatial relationships that accompany chemical change—changes in shape. Sometimes changes in shape influence greatly the understanding of the chemical process. Changes in biochemical systems are a good example of this. Other times the changes take place and there is no particular impact.

State. The state of a molecule within a set of molecules is the full inventory of energy relationships that exist. Heat and light are the two most common sources of energy that influence changes in state. Phase change is an example of this, where the relationship between molecules depends on the temperature of the environment. When molecules absorb or emit light this also involves a change in state.

Aggregation. The aggregation of molecules is influenced by a variety of intermolecular and intra-molecular interactions. Why do some salts dissolve in water and others do not? Why do some things mix while others do not? Forces of aggregation also strongly influence our understanding of biochemistry because, in general, multiple molecular units must spontaneously assemble in order for specific chemical reactions to be catalyzed. An understanding of drug design, including mode of action, relies heavily on understanding the relationships that exist in molecular clusters.

Concentration. When materials combine to undergo chemical reactions, large collections of molecules mix, colliding with one another. All measures of concentration express "the number of molecules per unit volume." Changes in concentration affect the number of collisions that can take place between the different substances. The higher the concentration, the more molecules of one substance will be able to collide with another. The greater the number of collisions, the greater the likelihood of a productive collision taking place. The effect of concentration on reactions is an important topic in understanding the particulate nature of matter.

In collaboration with the Center for Technology in Learning Group at SRI International (Menlo Park, CA), the ChemSense Studio has been created as a one-stop instructional environment designed around the pedagogical strategies that we have developed in the SSG program. The detailed design issues are beyond the scope of this discussion, and we will instead focus our attention on the implementation of this tool

in our introductory chemistry courses. A compilation screen shot is shown in Fig. 6; more information can be found at <http://www.chemsense.org>.

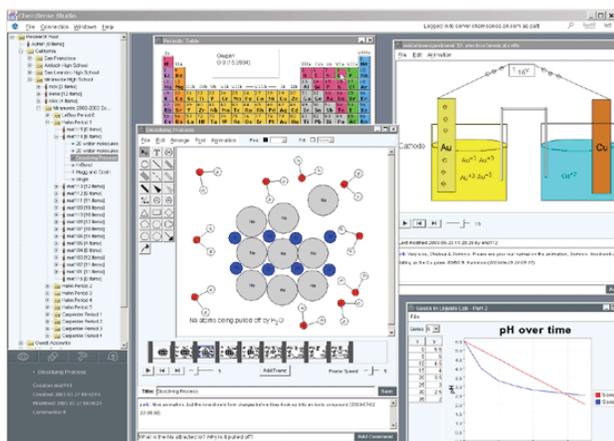


Fig. 6. ChemSense Studio.

VI. IMPLEMENTATION I.

Fall 2000 experiment to integrate Chemsense into lecture and laboratory

Our first implementation, during the Fall 2000 semester, involved 30 first-year students enrolled in the SSG program for the introductory organic course. The students, in teams of three, investigated structure-reactivity relationships in solvolysis reactions; specifically, the task was to investigate the rates of solvolysis of alkyl halides by monitoring the change in pH with Pasco probes. The teams were responsible for designing a series of experiments, predicting their outcomes, and then executing them. The implementation was designed to include little lecture-style instruction from the leader, as we wished to investigate the learning that could take place solely through the STUDIO.

To facilitate the design of the experiments, the students were provided with a list of potential substrates to choose from, and asked to pick a triad and explain what factor they hoped to investigate with their triad. Additionally, some groups decided to do the same triads as another group with an additional variable (different temperature, different solvent, etc.).

Prior to running the experiments the students had to explain in a variety of media formats what they thought the results would be and why. The first iteration was a simple textual explanation. In preparation for using some of the STUDIO tools, the students were then asked to create a 'storyboard' for their reaction, detailing on the molecular level what they thought would happen in their systems. These included not only the mechanism of the solvolysis, but also the predicted relative rates and any solvent reorganization. Finally, these storyboards were converted into animations using the STUDIO.

The primary driving questions in this study were:

(1) to examine the degree to which students would spontaneously represent changes along all five of the molecular representational dimensions when provided

with a tool (ChemSense Studio) that could easily support these, and

(2) to examine what differences students who participated in this integrated experience might reflect in their chemistry understanding compared with students who did not do so.

The curriculum materials were intentionally left unscaffolded in order to be able to assess the spontaneity with which students might respond along each of the five dimensions without receiving specific training or reminders.

Data and reflective comments.

A. Students were videotaped at a number of critical junctures as they performed their work.

In many places, the videotapes show students engaged in productive, self-correcting discussions about the chemistry. The need to think about multiple molecules was an explicit part of the student task. The availability of the ChemSense Studio environment permitted a task structure that would not have made sense without the explicit ability for constructing animations, for instance. In general, the students in the groups did a good job of working their way through many of the representational issues associated with the five dimensions. Because they were directed to consider the behavior of a multi-molecular system from the start, the students addressed and self-corrected ideas about chemistry that they would not have needed to encounter at all.

B. Student work was scored by two independent raters according to rubrics tailored to each of the five dimensions.

A series of scoring rubrics was created that each reflected the different levels of representation that one might depict in these phenomena. The rubrics were created to permit the customized analysis for the explanation of any chemical process. The rubrics are attached as Appendix B. In general, the students did not spontaneously extend their representations beyond the level at which the tasks were requested. Changes in connectivity were typically and predictably the richest dimension. This probably represents the fact that the course itself emphasizes changes in connectivity as the single way to explain molecular phenomena. For example, none of the students indicated a change in geometry that was at the level of their expected understanding. We think that this is because it was never linked (during instruction) as closely to the connectivity changes as was required in this task. The understanding, in other words, was probably segregated, required a trigger in order to elicit, and might mean that students are not seeing representations as molecular entities but rather still focused on the surface features. The use of multi-molecular explanations was triggered by the instructions. In general, these aspects of chemical reactions are rarely instructed in depth, even more rarely illustrated dynamically on a regular basis, and never, to our knowledge, constructed by students. The students generally incorporated state issues (Brownian motion of particles) as well as concentration issues (not all events happen simultaneously);

aggregation issues (solvation state of molecules and ions) were little considered. We reiterate that these observations of negative results (students do not spontaneously intuit the capabilities of tools) is an affirmation that scaffolded instruction and explicit practice need to be attached to the development of a software environment.

C. *An on-line quiz designed to assess the ability of students to understand dynamic representational information along the five dimensions was created. The subjects were (a) SSG students in the experimental group, (b) SSG students not in the experimental group, (c) volunteer students from the class who were not part of the SSGs, and (d) a small group of expert respondents.*

In general, there were not significant differences in the way the different groups of students performed on these questions. Even without having been through the process of actually constructing the various types of representations, students who had received only traditional instruction were able to answer these questions.

Our results are neither surprising nor remarkable. The curriculum and the representational tools need to be more explicitly linked, instruction in building up and linking the different representational dimensions needs to be designed and not haphazard, and the use of these tools probably needs to be extended over time. On the other hand, we have a valuable baseline for the unscaffolded version of this intervention, and demonstrated the ease of its integration into an existing curricular program.

This experience was a wholly unique one for both the students and their instructors. There are few examples in science education that have blended lab and recitation activities so intimately. Science laboratory exercises are commonly following 'cookbook' recipes from a manual, not student-initiated experiments. The students went through the entire process of 'doing science', from designing the experiments, predicting resulting, defending predictions, executing the experiments and analyzing and rationalizing the results. This process is one that many graduate students struggle with, but undergraduate curricula typically ignore these skills. It is the nature of a *project*, something that students become involved in and feel ownership of, that differentiates it from *assignments*.

VII. IMPLEMENTATION II.

Fall 2001 experiment to integrate ChemSense into the entire SSG program

Our second implementation, during the Fall 2001 semester, was to modify the existing SSG curriculum to utilize the ChemSense Studio. Students from 3 of the 8 SSG sections (Fall 2001) participated in this experiment. All of the weekly assignments were created and peer-reviewed by the students in ChemSense, without rewriting any portion of the curriculum. In fact, the student leaders alone were responsible for minor modifications to the assignments to suit and exploit the STUDIO. ChemSense allowed the leaders to think about how

to both present information and assign tasks that were normally restricted to simple paper-based answers.

In collaboration with a graduate student in the School of Library and Information Science, we also conducted a study of the ChemSense interface from a design standpoint. The interactions of students with the software during a simple task were compared for the students who had been using ChemSense versus those who had not.

The primary driving questions in this study were:

- (1) to examine the feasibility of integrating the ChemSense Studio with an existing curricular program of materials, and
- (2) to examine the interface usability for experienced and inexperienced users who were given a representative task, in order to provide user-based feedback to the design.

To date, we have begun to analyze the wealth of qualitative data generated in order to help answer these questions. For the remainder of this paper, we will simply present some of these reactions.

A. Experienced student leader.

From the perspective of our experienced student leader, having been both student and a leader in the SSG program, with and without ChemSense, its incorporation into the curriculum is "a significant step forward. Having the entire section's work available to me and to all of the other students was immensely beneficial. I could keep tabs on how the students were doing with the week's assignments, even sometimes catching potential pitfalls and cognitive traps before the students fell into them. It also seemed that the students had a greater self-imposed sense of accountability with respect to their work. Frequently students would ask questions about someone else's work prior to our meeting – the students were in fact using the tools available to them to peer review one another on their own.

"As a leader I used ChemSense in situations that are not possible in a paper-based classroom. On a number of occasions I would use my student's work to illustrate some concept, or to show unique ways in which others were using the STUDIO. Displaying student work in real-time is incredibly easy, and my students seemed to respond more when I used their work as examples as opposed to providing my own.

"There were, of course, problems. The software is still in its infancy, but is improving on an almost daily timescale. At the time, we had problems with the chemical drawing tools, as more robust packages were available to the students for this task, so the frequent procedure was to use another drawing package and then import the structures. People, both students and leaders, were concerned about the ease of cheating in such an electronic environment. There is no greater risk of such activities in ChemSense than there is over the Internet; it is a fact of our modern world.

"I truly believe that the benefits largely outweigh the costs associated with using ChemSense. Although there is a slight learning curve, for everyone involved, the freedom is astounding. Many curricular pedagogical decisions about how to and what material to present are probably based largely on tradition – tradition from when generating complex

multimedia files was either unheard of (10 or more years ago) or considered too time consuming and difficult for most students (5 years ago). ChemSense allows for such creation, and through my experience leading a section through a curriculum with the STUDIO on hand, many of these traditions melted away. In no way was I able to capitalize on each and every one of these, nor would it have been beneficial to my students to do so, but the door to such changes has certainly begun to open.”

B. New leader responses.

“There were several things that I liked about working with ChemSense, the first and most important being not having to deal with paper. It's really nice to access your students' work from wherever and not have to worry about losing their stuff. I also liked that people could access each other's work at any time - a feature which I think was underutilized but still interesting.”

“One of my big problems with ChemSense was not having paper to work with. Giving good constructive feedback is harder because you can't scribble in the margins and point to what you're talking about. Also, all the technical problems really took away from the experience. I think that if the software had been in better shape at the time, a significant portion of my problems would have disappeared.”

“One nice thing about ChemSense is that my students used it for other stuff besides chemistry. One kid did a class project using ChemSense and exported it because they had really nice flow chart boxes. He also posted other random files in his space that we could all see. I think if more people were using the software it could have been quite a hub for exchange.”

“In general my students complained about ChemSense (because of all the technical problems) but seemed to like the animation assignment. I think that this was by far the most valuable assignment we did with the software. The tool is easy to use and seeing the Newman projection rotate thru 360 degrees is much more useful than looking at stationary drawings.”

C. Student responses.

“I liked ChemSense. I would prefer doing the work on computer rather than by hand- it looks clearer and we can animate, etc. People who get into research or other careers in chemistry are going to be using computer programs, so they may as well get familiarity with it now.”

“Personally, I liked ChemSense. ChemSense was neat. I liked that. If I did all the assignments on paper, it would be messy; other people wouldn't be able to read my work as well. ChemSense compiles everything.”

“What was really nice about ChemSense was that you could look at everyone's work, and it was all easy to read, regardless of its correctness.”

“[ChemSense] offers a really nice way to learn about connectivity. Animating mechanisms also forces you to understand what's going on in a reaction. It's also a lot more convenient to be able to go on the computer and look at people's assignments, versus passing around sheets of paper with questionable handwriting and chair-drawing abilities during class to peer review.”

“By drawing it out on the computer, you get a clearer picture of what's going on. Also, ChemSense allows us to make easy corrections at the peer groups, which is good. By having it on the computer, you are forced to set time aside to do it (where as on paper you could keep putting it off because you can do that anywhere). The animations really help to visualize what goes on, so I think they are an invaluable resource.”

“I think that ChemSense, on the whole, has been a useful tool. It keeps things organized, and it certainly makes peer review a lot more interesting than the usual exchanging-papers routine. Turning in assignments is also much easier, and we get to see what kind of work the other students are doing. The things we have done with the existing drawing and animating tools are quite amazing; one can only imagine the future possibilities.”

“The thing I like about ChemSense is the ability to see the work of others while it is in progress. This greatly helps me in understanding the assignment and in formatting it. If everything is going to be done on the computer anyway, why not post it on the web, rather than just printing it.”

ChemSense definitely has its advantages and its disadvantages. It was a big help to be able to look at other people's work if I was having trouble. Copying was rarely an option because we always had different molecules so just following someone else's thought process seemed to help. Sometimes doing work with ChemSense meant doing it twice. Sometimes I would have to do things on paper first and then do them again on the computer. This helped cement ideas for me, but sometimes it was still a bit frustrating and time consuming.”

VIII. IMPLEMENTATION III.

Fall 2002 examining differences between ChemSense and traditional classrooms

Our third implementation, in the Fall of 2002 proceeded by adding a pretest, 2 quizzes and a posttest to the curriculum in addition to the existing assignments. A total of 152 students participated in the SSG groups divided between experimental and control groups. All of the students received the same pretest, quizzes and posttests. The students in the experimental sections answered via ChemSense while the control group used traditional pen-and-paper methods.

We are currently developing techniques of representational analysis to examine the students' responses. Our interest is in elucidating the differences, if any, between the responses from students using ChemSense and the students using traditional methods. Our method is to create a thematic diagram, which is a metarepresentation that facilitates comparisons of different types of student work.

A similarity analysis of the thematic diagrams produced for both experimental and control group work showed that when compared with the quiz questions, students' answers tend to represent themes the way they are represented in questions. That is, visual elements of questions are reproduced visually by students in their answers, while verbal elements are reproduced verbally. In addition, students' answers tend to differ thematically from each other when their

answers differ thematically from the quiz question. Students tend to create and use different themes visually than they create and use verbally.

In comparing the experimental and control groups, visually, the experimental group is more similar to the advanced students and textbook representations groups than it is similar to the control group. Verbally, there is no significant difference between the experimental group and the control group.

Our analysis of the data is continuing.

ACKNOWLEDGMENT

The authors thank their collaborators at SRI International for helping to make ChemSense a reality. They also thank the University of Michigan Department of Chemistry and the Honors Program for continued support over the years. They also thank deeply the Chemistry 210 and 215H students and leaders who have participated in the development of this work over the years. A. Kiste is supported by a US Dept. of Education GAANN fellowship.

This material is based upon work supported by the National Science Foundation under Grant No. 0125726. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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