Design and Use of Process-Oriented Guided-Inquiry Activities
in General Chemistry

David Hanson and Troy Wolfskill
Department of Chemistry
Stony Brook University

Introduction to POGIL / LUCID Activities

Over the past several years there has been a growing body of computer-based materials, which are delivered on CDs or over the web, that are intended to enhance traditional teaching methods aimed at presenting information and evaluating student performance on assignments or examinations. For example, texts and lectures are enhanced with multimedia and interactive features, and homework assignments are supplemented with instant feedback or are personalized and computer graded. Virtual lectures also have appeared. Digital libraries, such as Merlot and the National Science Digital Library (NSDL), further encourage the development of such materials and serve as repositories and distribution centers for learning objects.

Learning objects are a new way of thinking about curriculum materials. They derive from computer programming objects that are pieces of software that can be reused in different contexts.[13] In promoting learning objects and establishing digital libraries, organizations have identified specifications and characteristics of learning objects, and authors are expected to tag their materials with metadata providing descriptive information characterizing the learning object, its intended audience, and the pedagogy it supports.

While we value these efforts to provide stimulating and accessible learning materials, there are challenges remaining that need to be addressed in order to meet the needs of today's students. In our experience, learning objects for General Chemistry generally are lacking in one or more of the following areas.

- The design is not based on a complete cognitive model of how most students learn chemistry best. By learn chemistry we mean develop a conceptual understanding and the ability to apply this understanding in solving problems. The design of too many learning objects is based on the model of learning preferred by many students: tell me and I'll memorize it.
- The materials do not explicitly include the development of learning process skills that are essential for success in courses, college, and careers.
- The materials generally are not comprehensive. They do not come in sets that span two semesters of General Chemistry, and it is unlikely that a complete set of materials assembled from a variety of sources for two semesters would form a coherent package. It is more likely that they would lack uniformity in almost everything one can imagine. Of most importance would be the lack of support for a consistent pedagogy or philosophy and the absence of a uniform format and familiar look-and-feel. Variety can stimulate learning, but too much variety and difference in the format of learning objects can produce cognitive interference in the learning process. Valuable time is spent repeatedly on trivial issues, such as identifying what the activity is about, where is the necessary information, what is to be done, and how are results reported.
- Individual objects are not complete. They usually need to be augmented in some way to fill a class session, and generally little or no help is provided to guide the instructor in implementing
the learning object successfully in the classroom. Having a dynamic model or other visualization of a chemical process can result in maximum learning only if the instructor knows how to use it in the classroom. Such a learning object needs to be connected explicitly in a planned classroom activity to a complete cognitive model of how most students learn chemistry best. It is not sufficient to have a neat interactive animation and tell students to play with it.

- The materials are not field tested. While they may have been reviewed by professionals, rarely do they contain the perceptions of instructors and students who have used them or quantitative measures of how well they produce the intended learning outcomes. Effective learning activities can only be assured if they have been field tested, assessment data collected, and the data analyzed and used to revise and improve the activities.

The materials to be developed at this workshop will address these issues by producing innovative web-based activities that span two semesters of General Chemistry. The design of the activities will originate from the current research-based understanding of how most students learn chemistry best, incorporate the development of key process skills that students need for success, and provide a complete template for use of the activity.

**A Cognitive Model for Learning**

The traditional model for teaching chemistry has been and continues to be based on lecture and textbook readings in spite of the rapid growth of information technologies and the plethora of technology-based materials that have been produced. In this model, the instructor serves as an authority providing information, and there is little student-teacher interaction and almost no student-student interaction. The lecture model presumes that all students need the same information presented orally at the same pace in an impersonal way. Although lecturing is an efficient way to present information, relay personal perspectives, and possibly motivate the audience, it does not result automatically in efficient learning.\[1-6, 14\].

Many students miss the human interaction and exchange of ideas in a lecture format\[7\] and do not see the relevance of what they are learning. Consequently they develop negative perceptions of chemistry and science\[8\] and are lost from the science human resource pipeline early in their college careers.\[7-10, 15\] Students remaining in science often have difficulties in applying knowledge to solving textbook, examination, and eventually to real-world problems. Many simply read about the solutions in manuals, on posted answer sheets, or watch problems being worked in recitation sessions. These students memorize algorithms for solving problems and do not understand and apply concepts. Also, students in a university setting mostly work independently and gain little experience in teamwork and associated skills needed in the workplace.\[7-11\]

Contemporary learning theory and classroom research provide a cognitive model for learning and suggest a different format for instruction. The premises of this model are that most students learn chemistry best by -

- Constructing their own understanding from information in a process that involves prior knowledge, experiences, preconceptions, skills, attitudes, and beliefs.
- Following a learning cycle consisting of exploration, concept invention, and application.
- Visualizing and connecting macroscopic, particulate, and symbolic representations.
- Discussing and interacting with others.
- Reflecting on their progress in learning.
• Assessing their performance.

These six components of the model are justified briefly in the following paragraphs.

**Constructing Understanding.** In the contemporary view of learning, people construct new knowledge and understanding from what they already know and believe. This theory does not preclude lecturing because listening to a lecture involves attempts to construct understanding, but there is considerable evidence that improved learning results when students are actively engaged and must struggle with issues on their own rather than being told how to resolve them.[3-5, 16, 17]

**The Learning Cycle.** As described by Lawson, a learning cycle has three phases: an exploration phase, a concept invention phase, and an application phase. Research has documented that learning is most effective if the phases are presented to the learner in that order. In the exploration phase, students become familiar with a model that represents the concept to be learned. In the invention phase, the concept is introduced or students are guided to its discovery. In the application phase, the concept is applied to new contexts.[18-20]

**Visualizing and Making Connections to Multiple Representations.** Visualizing and understanding chemical phenomena require representing these phenomena in three ways: by using macroscopic, particulate, and symbolic representations. A macroscopic representation is a model of the world based on direct observations. A particulate representation is a model based on the behavior of atoms and molecules. A symbolic representation is a model depicted by pictures, words, mathematical symbols and equations, chemical symbols and equations, tables, and graphs. The facility with which a student moves between these representations can indicate the degree of understanding of a chemical phenomenon.[21-25]

**Discussing and Interacting with Others.** Over 600 research reports compare the effectiveness of competitive, individualized, and cooperative learning structures. Comprehensive reviews and analysis of this research have been published.[26-28] Based on this research, students working in learning teams can be expected to learn more, understand more, remember more, feel better about themselves and others, have more positive attitudes regarding the subject area, course, and instructors, and acquire critical thinking skills, cognitive learning strategies, and other process skills that are essential in the workplace. Because students work together to construct understanding and share ideas and strategies, their performance as individuals, e.g. on examinations, improves.[6, 29-33] Research has shown that learning groups are particularly effective for women and other nontraditional students in science.[11, 12, 34] because this approach addresses the inhibiting feelings of isolation and competitiveness that many report.[11, 12] The importance of discussion and social interactions in the learning process also has been emphasized in the recent National Research Council report.[16]

**Metacognition and Self-Regulation.** Metacognition refers to the learner’s awareness of his or her own knowledge and learning process. It involves reflecting on what has been learned and on the learning process itself. Self-regulation refers to the learner’s ability to identify successes, strengths, and improvements that are needed in their performance, and then develop and implement a plan to improve. Such reflection and self-assessment are essential to produce learners who continuously improve their learning process.[16, 35]

**Research-Based Activity Design**

The above research-based cognitive model maps into the design for learning activities. Each activity consists of the following sections: Orientation, Exploration and Concept Invention,
Application, Reflection, and Self-Assessment. These components of an activity are described in the following paragraphs.

An orientation prepares students for the learning process. Activities begin with a motivation for learning both within the course and beyond. Performance criteria (also known as learning objectives) are identified to set the expected level of mastery. New concepts and vocabulary are listed. Prerequisites are identified, and the students' prior knowledge assessed with one to three questions.

A model is provided for the students to explore. A model is any representation of the concepts that are to be mastered in the activity. As appropriate, the model contains macroscopic, particulate, and symbolic representations. Questions guide the exploration of the model appropriate to the learning objectives.

LUCID activities are delivered on a computer so the models can be as dynamic and interactive as is appropriate. The models can feature buttons, knobs, virtual instruments, animations, and other devices to support the exploration of relationships through parameter variation.

As a result of the exploration concepts are invented. Questions guide students to the concepts present in the model. Rather than presenting information as in texts and lectures, the aim is to develop conceptual understanding by engaging students in guided discovery. This process is structured by supplying questions that compel students to think critically and analytically as they interact with computer-based models that embody the key concepts.

The new knowledge then is applied. Once the concepts are identified, single-step exercises reinforce the concepts in a context similar to the model. A Got It! subsection provides concept questions to assess understanding and the ability to connect the macroscopic, particulate, and symbolic representations present in the activity. Problems then provide applications of the concepts in new contexts that require higher-level thinking skills such as analysis, transference, and synthesis.

The importance of posing problems and questions to enhance thinking skills and reveal misconceptions has been discussed in the literature.[29, 33, 36-45] By paying particular attention to developing conceptual and context-rich problems, and by relating chemistry to current real-world issues, these concerns can be addressed. Experimentation with various types of problems, problem-solving strategies, and expert methodologies coupled to reflection activities helps students to integrate the conceptual, analytical, and procedural aspects of problem solving and become more effective and efficient problem solvers.[46]

It is amazing how much thought can be produced simply by omitting information, requiring assumptions, including superfluous information, or having multiple parts to a problem. In order to improve problem solving skills, it has been found that it is necessary to have students focus on providing a plan for solving a problem and a problem solution rather than on a numerical answer. It has also been found that students can solve a problem in a familiar context (e.g. one dealing with coins) and fail to solve essentially the same problem when it deals with isotopes. Consequently, specific activities must be included to help students develop the skills they need to transfer their knowledge from a familiar context to a new one,

Each activity closes with reflection on learning and self-assessment of performance. When students are asked to reflect on what they have learned, their knowledge is consolidated, and they see that they have been rewarded for their hard work. We believe that self-assessment is the key to improving student performance. When people recognize what they have done well,
where they need to improve, and develop strategies to achieve these improvements, they are both encouraged and motivated to work toward that goal. Examples of reflection and self-assessment questions have been published.[47]

**The POGIL Classroom**

The above discussion describes a design approach for activities and the research-based cognitive model of learning on which these activities are based. The activities will be appropriate for use in several contexts. They can be used as part of a lecture, in recitation sessions, as homework, with learning teams, or for individual tutorials. One context that we believe is particularly effective is the POGIL classroom.[49]

The focus on process in the classroom [50, 51] represents a synthesis of several issues being discussed in the education community. It involves combining cooperative learning, guided discovery, critical and analytical thinking, problem solving, reporting, metacognition, and self-regulation into a coherent package. The objectives are mastery of subject content and the development of performance skills. The process model incorporates Bloom’s taxonomy of educational objectives,[52] and promotes the development of students from Piaget’s concrete operational stage toward the formal operational stage.[53-56] Its foundation is the tenet from the constructivist theory of learning that learners must construct their own understanding or knowledge from information in a process that utilizes prior knowledge, previous experience, preconceptions, skills, attitudes, and beliefs.[3-5, 16, 17]

The benefits of cooperative learning cannot be achieved simply by placing students in groups, giving them an assignment, and telling them to work together to complete it and teach each other in the process, as many faculty will testify.[57] The five elements that have been identified as being essential for real collaboration and successful cooperative-learning groups are positive interdependence, individual accountability, promotive interaction, collaborative skills, and self-assessment.[6]

**Enhancing Activities with LUCID**

The computer-based activities can be delivered via the web either within or independent from course management systems such as Blackboard and WebCT. The activities will be modified appropriately to produce text-based activities as well. For these written materials, the film clips and interactive models will be replaced by static models. All of these delivery formats would require students to use a pencil and paper to record their responses to questions, and the sharing and review of responses between teams would require oral presentations, a chalkboard, or exchanging reports.

A number of enhancements are provided by deploying the activities within our LUCID Learning and Assessment System.

- Both team and individual responses to questions, exercises, and problems are automatically stored in a database. Each student thus is provided with both an individual and a team learning portfolio that can be accessed both during and after a course, or can be downloaded for review outside of the system.

- Responses to open-ended questions, notes on solutions to exercises, plans for solving problems, and detailed solutions to problems can be instantaneously shared for peer review. In this process, all students view their response along with the response of a randomly selected team, with all teams viewing the same set of responses. Teams must then note whether they agree or disagree with the reported response, and submit this review for storage in the database.
Teams can then retrieve an overview of the peer review in the form of a bar graph that indicates the relative numbers of teams that agree or disagree with each response. The teacher can use this information to promote inter-team discussion. In addition, the teacher can agree or disagree with each reported responses, or agree with reservations. Discrepancies between the teacher and student reviews can be retrieved from the database for analysis.

- Teams can submit their answers to exercises and problems for analysis and feedback. The number of attempts for each response is logged to the database, as well as the time taken for each attempt. Since the LUCID response analysis system is based on multi-dimensional assessment, teams can be informed of what they have done correctly without supplying them with the correct answer or a detailed solution. For example, if students submit a molecular formula with appropriate element names but inappropriate subscripts, they are informed that the response is incorrect though the element names are correct.

- Since the LUCID multi-dimensional assessment system is able to identify which competencies have and have not been met by a particular response, the development of competencies within an activity can be tracked and analyzed.

- Using the tools provided in LUCID, students can construct responses as text, symbols, data tables, graphs of data or functions, pictures or Lewis structures. All of these can be submitted to the response analysis system for analysis and feedback.

- Self-assessment activities are accompanied by performance distributions that inform students of their performance with respect to other teams in the areas of the quantity and care with which the work was done as well as the quality of reported responses and reviews of other teams’ reports. Competency reports are also provided in this context.

- As self-assessments are stored in the database, teams can periodically review the areas for improvement they have identified and assess the effectiveness of their strategies and efforts to improve.

- By employing LUCID for online homework and quizzes or to prepare paper-based midterm and final examinations, a full record of the development of student competencies throughout a course is generated. This information can be used by both students and instructors to identify areas for improvement in learning, teaching, or materials.
Bibliography


Bibliography


