Teaching Introductory Chemistry using Concept Development Case Studies: Interactive and Inductive Learning

PAPER

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At Rice University, we have used an unusual approach to introducing fundamental chemical concepts in the introductory General Chemistry course. New concepts are developed through inductive reasoning in a series of case studies. These are designed to complement an interactive or "Socratic" classroom technique, in which the focus is on active intellectual engagement of students in a discussion of chemical concept development. The methods are described in detail, and results are presented which demonstrate the effectiveness of the approach in developing a deeper understanding of chemistry as well as critical thinking skills.

Introduction

The standard approach to teaching chemistry at the introductory college level has not changed significantly in decades. Material is introduced in lectures, which typically are expository and explanatory statements of concepts and applications. Homework assignments and exams are, in the main, skill tests requiring numerical or descriptive problem solving and factual recall. A glance at any of the many available General Chemistry texts reveals clearly the pervasiveness of the traditional approach.

The flaws in the standard approach are both familiar and well documented[1,2,3]. Students perceive it as boring and without purpose. Furthermore, even after instruction, students retain significant misconceptions about many fundamental chemical principles[4] including the meaning of an atomic view of nature[5], the nature and origin of bonding energies, the significance of the octet rule[6], and the differences between chemical and physical properties[7].

It has been established that most students learn much more effectively in active and cooperative learning environments[8] in which they develop new ideas logically from simple principles by a process which involves inductive reasoning[9-11]. By contrast, the lecture format is almost entirely passive, with students spending their class time simply transcribing the lecture, disengaged from the intellectual content[12]. New concepts are presented *fait accompli* which encourages students to accept ideas that they do not understand, and to commit challenging material to memory rather than try to understand it and integrate it with their existing knowledge.

The limitations of the traditional lecture have not gone unnoticed, of course. A number of approaches have been introduced to initiate what has been termed 'active learning'. These approaches include peer instruction[13], concept question discussion[12], discovery laboratories, team assignments, and 'minute' essays. Other innovations have focussed on methods for making the explanations easier or more illuminating, particularly in revealing challenging concepts such as the particulate model of nature. New textbooks typically focus on new problem solving approaches and examples. Computer animations of simulated molecular processes have certainly been found to help students understand particulate concepts. Video presentations make chemistry more visual and real. Computer tutorial programs provide more individualized instruction than is possible in the large lecture format. These are very important modifications to the traditional pedagogy and their widespread incorporation into chemistry instruction should be encouraged. However, in most cases these cannot fully address the fundamental problem, since they are superimposed on the basic structure of the traditional declamatory lecture.

We decided to go a stage further and devise a course in which the lecture itself was a truly interactive experience. This required the design of a suitable resource to support the student learning. We describe here the development and use of the resource which we developed for this purpose.

Preparation of Case Studies in Concept Development

Our initial analysis of the problems faced by students suggested that, although many chemical processes are familiar in everyday experience, the chemical concepts underlying these processes are themselves unfamiliar. This is because chemical models are inherently molecular, outside the range of everyday experience, and therefore models are far from intuitive. Our goal was to help our students to develop the chemical intuition which would allow them to bridge the gap between the familiar processes and the unfamiliar chemical concepts and models. We therefore used the same inductive reasoning method as was used originally by chemists to develop the chemical models in general use today. This means introducing each major chemical concept through discussion of relevant experimental observation, and logically developing a model to describe these observations.

The resource we developed had to be suitable for the General Chemistry course at Rice University which is taken by between 250 and 300 students in a single class section with a single instructor supported by Teaching Assistants. The class meets three times per week, 50 minutes per day, for 15 weeks in a semester. In addition, students meet once per week in small discussion sessions of 30-40 students. Most spend 5 – 9 hours per week of their own study time on this course including reading, homework, discussion, group review etc. In these regards, the course at Rice is similar to most General Chemistry courses in the USA.

With this in mind we prepared nine case studies of the development of chemical concepts. These are listed in Table 1 and they are provided in textbook format for the students[14] and are available via the web (see section on Availability). This is not the only text used by students on this course since it is concerned primarily with the development of the concepts. For applications, students rely on a more conventional text, 'Atoms, Molecules, and Reactions'[15]. Student surveys (see later) reveal an extremely strong preference for the 'Case Studies'. Each study introduces new concepts using a series of seven steps analogous to those typically used to develop any new concept in science. These are shown in Table 2.

The material in each of the nine case studies is completed in two or three of the 50 min slots. This leaves two or three other 50 min slots (which are devoted to appropriate applications and problem solving), one or two discussion sessions (devoted about half-and-half to review/discussion of the class material and to reviewing homework answers) and homework. Homework is assigned weekly, typically consisting of 5-8 essay questions covering the concept development studies, and an additional 5-8 standard objective problems to solve. It is due in at the Monday class; it is graded that afternoon by the teaching assistants, and returned that evening during discussion. The primary roles of homework are as a study guide and as practice in writing short paragraphs about chemical concepts.

The style and structure of the case studies is illustrated by a description of Case Study 3 'Periodicity and Valence'. The full text can be viewed on-line (see Availability).

In this case study, the aim is to develop the concepts of a valence shell and the octet rule as means of predicting atomic valence. These concepts form the basis of Lewis structures of molecules, perhaps the most significant of the chemist's theoretical models. The case study is designed both to bring meaning to these models and to encourage students to distinguish experimental facts from conceptual interpretation. It uses the experimental facts which were actually used to develop these concepts, and so introduces an historical perspective to their learning.

The Foundation (step 1 in table 2) is Case Study 1 (Atomic and Molecular Theory). Therefore it is assumed that students understand that relative atomic masses have been measured and the valences of the elements are known from molecular formulae. The principal Question (step 2) posed is what property of an atom determines the valence of the atom. The first Experimental Observations (step 3) of the properties of elements reveal the grouping of elements by physical and chemistry properties and from these groupings the Periodic Law is developed with emphasis on the periodicity in the principal valences of the main group elements (this is the Model Building of step 4 and leads to Further Questions).

In order to develop a model for periodicity, 'Further Observations' are needed. At this point the results of electroplating experiments are used to demonstrate that atoms contain particles of negative charge, i.e. electrons. This leads to the 'Further Question' of how these charges are arranged in an atom, a question which is answered by analysing Rutherford's observation of the scattering of alpha particles by gold atoms. Inductive reasoning leads to the familiar nuclear model of the atom.

The atomic model remains incomplete, however, until the number of electrons in each atom has been determined. Here we use the actual experimental evidence from Moseley's measurement of the atomic X-ray emission frequencies. The number of electrons shows that elements with the same

Table 1 List of case studies

The Atomic Molecular Theory – development of the theory from the Law of Definite Proportions, the Law of Multiple Proportions, the Law of Combining Volumes, and Avogadro's Hypothesis.

The Kinetic Molecular Theory – observation of the gas laws, derivation of the Ideal Gas Law, analysis of deviations from ideality, development of the postulates and conclusions of the Kinetic Molecular Theory, and interpretation of temperature in molecular terms.

Periodicity and Valence – this is discussed in the example above.

Chemical Bonding and Electron Pair Sharing – development of the Lewis structure model of chemical bonding from observations of molecular stability, bond lengths and bond strengths, development of the concept of resonance, observation and analysis of ionic versus covalent character, development of the concept of electronegativity.

Properties of Polyatomic Molecules – observation of molecular geometries, development of Valence Shell Electron Pair Repulsion model, observation and analysis of molecular dipole moments.

Atomic Structure and Valence – observation of quantum mechanical behavior in radiation and matter, development of postulates of quantum atomic theory, analysis of electron configurations, theoretical analysis of the Periodic Table and valence.

Chemical Bonding and Molecular Structure – development of quantum behaviour of electrons in molecules, observation and analysis of diatomic bond strengths, development of the molecular orbital energy level diagrams and the concepts of bond order and paramagnetism, analysis of molecular geometries, development of the concept of hybridization.

Energetics of Chemical Reactions – observation of specific heats of materials, observation of chemical reaction heats, development of Hess' Law and the concept of state functions, application of Hess' Law to formation energies and bond energies.

Spontaneity of Chemical Reactions – observation of spontaneous change, relationship of spontaneous change to probability via Boltzmann's equation, observation and analysis of absolute entropies in terms of Boltzmann's equation, development of the Second Law of Thermodynamics, observation of spontaneous phase separation in liquid mixtures, development of the concept of free energy.

Table 2 The process of concept development

Foundation: We first define a set of material on which the remaining observations and developments will be based. This directs the students to concentrate on relevant material.

Questions: The ideas presented in the foundation produce a group of open questions for discussion. These questions might arise from observations that are not fully explained by the foundation or that even appear to be inconsistent with the foundation. Or they might arise from a need to further clarify or detail a previously developed model.

Observations: Chemistry is inherently an empirical subject, based on actual observations of natural processes. This is most clearly revealed to students when they begin with the relevant experimental observations which lead to a model. In our concept development studies, we use (whenever possible) the actual experiments which were used historically to develop each chemical concept.

Model building: The appropriate scientific response to a new set of experimental observations is to begin assembling a model which is consistent with and accounts for the observations. "Occam's razor" is introduced in practice, as students are taught to seek the simplest model to account for the observations.

Further questions: As is familiar to research scientists, each new model often presents more new questions than it answers. A significant part of the utility of the new model, indeed, is to suggest directions for further experiments and observations.

Further observations: These might be logical extensions of the previous observations. They might also be, as often occurs in science, unrelated observations which, when combined with the tentative model, lead to further progress in developing a model which leads to deeper understanding.

Model modification: Additional observations permit us to refine a model, adding detail, removing ambiguity, or establishing limits of applicability. The process of questioning, observing, and model building is repeated iteratively until the original questions are satisfactorily answered.

valence show a periodic variation in their number of electrons. This quickly leads to the conclusion that the electrons in atoms are grouped into shells, including a valence shell which determines the chemical reactivity of the atom. The periodicity of the elements also permits determination of the number of electrons in the valence shell. Combining this with the known valences of the elements produces direct observation of the octet rule for main group elements.

This very brief description does no more than illustrate the Case Studies in Concept Development and demonstrate that both the experiments and the reasoning are within the grasp of introductory chemistry students.

Using the Case Studies

The students are introduced to the course 'rules' at the beginning of the course which are summarised in Table 3.

The main objective of the classroom sessions is to encourage students to verbalise in their own terms the reasoning which leads to the understanding of the concepts developed in the Case Studies. The application of the course rules (table 3) helps to ensure the involvement of the entire class. Other techniques are helpful too. Once per class session, rather than calling on a volunteer to answer, students are asked to answer the question to a neighbour. The buzz of noise which always accompanies this request is a testimony to its effectiveness. It gives everyone a chance to answer, particularly students who are too shy to speak in front of a large group and it lets students check their answers before volunteering to speak up. A further incentive to volunteer is that students receive extra credit for answering questions; even though each answer amounts to only about 0.15% of the credit for the course grade it appears to be sufficient to encourage participation. The real key is to make eye contact with the students to encourage them to attempt an answer. All answers are rewarded, even if incorrect, and no answer is ever ridiculed.

The question and answer format encourages active participation in the learning process and leads to genuine classroom discussion (even in a class of 250 students). Students frequently respond to an answer by correcting it (or providing a different answer), by clarifying each other's statements, or by extending each others' line of reasoning. In this way the formal presentation of the procedure of concept and model building given in the Case Study is transformed into an active learning process. The instructor leads the students through the steps, but they have the opportunity to develop their own understanding of each new concept in terms which make sense to them. This is a crucial step in the learning process according to the Constructivist Theory of learning[16].

In the seven years during which these case studies have been used it is rare to have less than 10 students raising their hands, and there has never been an occasion when none has offered an answer to a question. Typically, the first question posed in the course results in 40 – 50 volunteers keen to provide an answer. Throughout the course a typical number would be 20 or more. It is not possible in a class of 250 to ensure 100% participation. Our surveys tell us that about 1/3 of the students raise their hand every day or almost every day. About 60% of the students raise their hands at least occasionally. Only about 15% of the students say that they never participate at all.

The emphasis on active involvement and inductive

Table 3 Summary of the course rules.

Students study an assigned part of the case study (typically 1/3 to 1/2 of one of the Case Studies) before each class;

During each class the instructor guides inquiry and conclusions by asking appropriate questions;

Students are awarded marks for participation in class discussion;

Students wishing to answer a question must raise their hand and wait for the instructor to invite an answer;

Answers called out are ignored;

The instructor always leaves a gap of at least three seconds before selecting a student to give an answer;

reasoning are reinforced by the assignments given to students in both homework and examinations. If assignments follow the standard problem solving exercises, students rapidly learn to disregard 'extraneous' material about how the chemical concepts were derived. Therefore, questions on homework must challenge the students to explain the logical connections between experimental observations and theoretical models. Limitations of these models must be explored, and contrasting results must be considered to verify the limitations. Similarly, exams must ask for descriptions of relevant experiments along with logical reasoning leading to conceptual development, or must ask for rationalization of experimental observations on the basis of the models developed. Of considerable significance is that these homework assignments and exam questions challenge the students to write clearly, logically, and articulately about scientific concepts, which is a rare opportunity for most university students[17].

The mark for the course is based on examinations, on homework, and on student participation. There are three ninety-minute midterm examinations and a three-hour final examination each composed of about 2/3 concept development essay questions and 1/3 objective questions and problems to solve.

Student Feedback

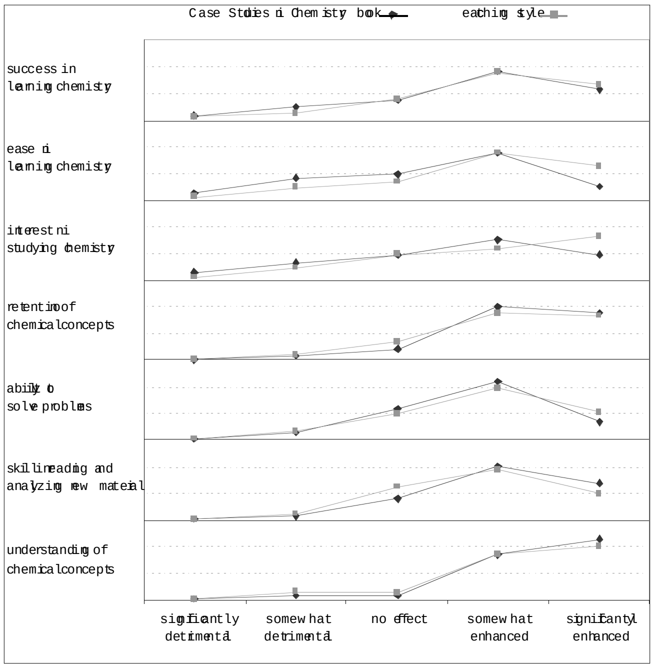
We have analysed the successes and failures of the interactive and inductive learning approach at Rice with a variety of instruments, including extensive end-of-semester surveys and comparisons of pre-instruction quiz with post-instruction exam. We also have anonymous testimonials from course evaluations and exit surveys[6,18].

The opinion surveys are strikingly positive. In each of the past seven years, we have asked students for the contribution of both the concept case study approach and the Socratic teaching approach to various elements of success in instruction. The results for the Fall semester of 1999, shown in Figure 1, are representative of these results over the years. For example, when asked for the contribution of the text 'Case Studies in Chemistry, to their understanding of chemical concepts, 51% of the students responded that their understanding was 'significantly enhanced', and an additional 39% said that their understanding was 'somewhat enhanced', a remarkable 90% positive reaction at the end of the semester. Figure 1 clearly reveals that the great majority of students feel that the case study approach with Socratic teaching enhances their retention of chemical concepts their skill in reading and analysing new material, their ease in studying chemistry, and their success in studying chemistry.

One might be concerned that the enhancement of understanding of chemical concepts comes at the cost of problem solving ability. However, Figure 1 shows that 65% of the students feel that their problem solving ability was enhanced by the concept study approach, presumably because it is easier to work problems about concepts which are understood clearly.

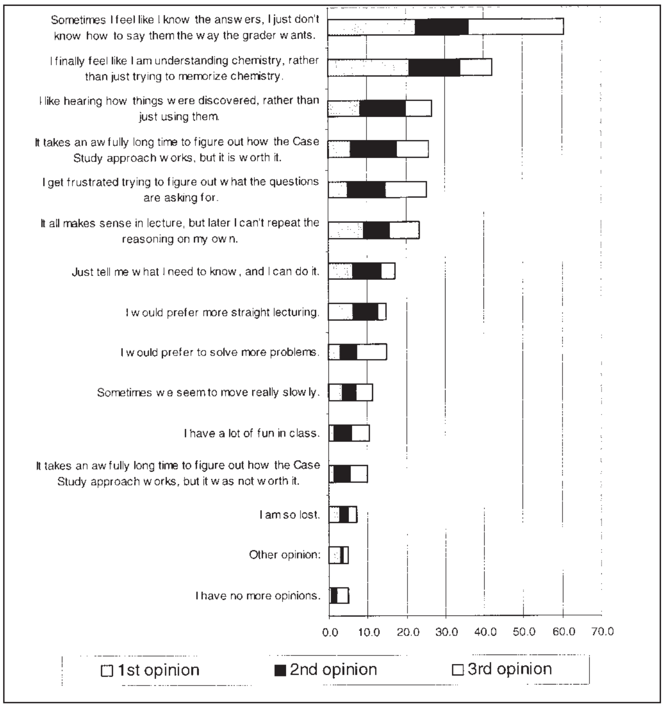
As a means of getting detailed and systematic opinion data about the concept development case study approach, we have

Figure 1



Exit survey results from General Chemistry (Chem 121) at Rice University for the Fall Semester of 1999. Students were asked to describe the contributions of both the Case Studies in Chemistry book and the Socratic teaching approach to their learning in the different categories on the vertical axis. In each category, the axis runs from 0 to 150 students, with grid lines at 50 and 100 students. The total number of students in the survey is 221.

Figure 2



Exit survey results from General Chemistry (Chem 121) at Rice University for the Fall Semester of 1999. Students were asked to select from the list of opinions on the left the three options with which they most strongly agreed. The horizontal axis is percentage of students selecting that opinion. The total number of students in the survey is 221.

offered students a list of 13 oft-quoted opinions, of which some are negative and some are positive. We then ask the students to identify the opinions with which they agree with most strongly, next most strongly, and third most strongly. The results for the Fall 1999 class are shown in Figure 2.

The data show that there are two primary popularly held opinions about the approach. The most popular opinion is that "Sometimes I feel like I know the answers, I just don't know how to say them the way the grader wants". This apparently negative response is a potential cause of disquiet which we discuss in the next session.

The second most popular opinion is positive: "I finally feel like I am understanding chemistry, rather than just trying to memorise chemistry." This sentiment runs in parallel with the third and fourth most popular opinions, "I like hearing how things were discovered, rather than just using them," and "It takes an awfully long time to figure out how the Case Study approach works, but it is worth it." In our experience, then, the students appreciate the opportunity to see beneath the surface of chemical concepts and to participate in scientific reasoning, even if they are concerned about the impact that these discussions may have on their grades.

In the light of some known difficulties which students experience, we have begun a long-term systematic study of student learning in General Chemistry by comparing student performance on pre-instruction diagnostic quizzes ('pre-test') with performance on midterm and final exams ('post-test'). Some results for the pre-tests given in Fall 1998 are described elsewhere[6], and a full analysis of pre-test post-test correlation will be published. Here we cite two examples of improved student performance following instruction via the interactive inductive learning approach.

First, students often show confusion over whether the process of bond breaking requires the input of energy or results in the release of energy. We have found dramatic improvement in student understanding of bond energetics following interactive inductive learning. In a pre-test multiple choice question, 34.7% of students correctly said that "when breaking a bond, energy must be added", whereas 24.4% believe that "energy must be released" and 40.9% believe that "the energetics depend on the circumstances." After interactive case study instruction we found that 74% of our students correctly describe the energetics of bond breaking. Furthermore we found that 50.6% of our students can correctly or nearly correctly describe in detail the disposition of the absorbed energy in terms of changes in energies of the bonding electrons, thus demonstrating a depth of conceptual understanding of bond energy. In direct contrast, a recent study at the University of California demonstrated that traditional lecture instruction and problem solving has little if any effect on students' misconceptions about bond energetics. However, these researchers also found that interactive teaching in a control group did improve understanding significantly.

As a second example, students often apply the fundamental tenets of Valence Shell Electron Pair Repulsion theory incorrectly. For example, on pre-test quizzing, 35% of our students believe that NBr_3 molecules have trigonal planar geometry, and 37% attempted to predict the geometry by considering only the repulsion between N-Br bonds. (The question we asked was developed by Treagust and coworkers[19,20], who found similar poor performance amongst high school chemistry students on post-instruction quizzes.) By contrast, following instruction via the case study approach, 84.7% of our students could completely correct all of the errors in a given statement that "In Nitrogen Tribromide (NBr_3), the three N-Br bonds are identical. The three electron pairs in these bonds repel each other equally, resulting in a planar molecule with equal 120° bond angles."

These two pre-test post-test comparisons reflect a fraction of the data we have available, all of which lead to the same promising conclusions. Students learn chemical concepts very effectively when they are taught interactively using concept development case studies, and they are also able to apply these concepts in solving chemical problems.

Discussion

The approach described in this paper is based on two key principles. First, effective learning requires intellectual engagement of students in the instructional process. This requires an active learning environment, but it also requires textual materials which complement active learning, so that discussion of chemical concepts is possible. Second, students learn concepts far more effectively when these concepts are developed via observation and inductive reasoning, rather than in expository prose. This requires a textbook which presents the experimental basis and reasoning behind chemical concepts, rather than simply a statement of these concepts along with problem solving applications. After seven years of experience of interactive teaching, using our textbook of Case Studies in Concept Development as our main reference source, we believe that our principles have been vindicated. Furthermore, we believe that our approach goes some way towards meeting the point made by Kooser and Factor[21] that we have an obligation to give our students "*a more realistic picture of the scientific enterprise in all its ramifications*".

There are some challenges associated with teaching interactively as described here. Not surprisingly, we move through our material somewhat more slowly, so a smaller number of topics can be covered per semester. In our view, that price is well paid, in that we much prefer to have our students cover a smaller amount of material that is well understood than a larger amount of material that is not understood. We also note that the course as taught is more labour intensive than one taught with an emphasis on lectures and problem solving. Since homework and exams do not typically have objective answers, they cannot be graded electronically. As such, a great deal of effort is required by the teaching assistants to grade verbal answers to concept questions.

A major question for us when we started using this approach was whether the focus on chemical reasoning would compromise the student's ability to solve traditional problems. We have combined our exercises in chemical reasoning with traditional problem solving and descriptive chemistry, since these are also important components of a chemical foundation. Our conclusion based on our observation of the students and on their responses to our questionnaires is that teaching chemical reasoning is a very effective way to teach chemical problem solving.

As far as assessment is concerned, we recognise the problem of students feeling that they know the answer but not being sure what the grader wants. To some extent this reflects the fact that most students have come to expect that, in science, there is a single right answer, and producing that answer on an exam is a guarantee of a good grade. This is consistent with the dualist mentality (everything is right or wrong, black or white, etc) which is associated with the first stages of intellectual development described by Perry[9]. The approaches used at Rice run counter to this expectation and indeed are intended to help the students to progress to higher levels of development. The difficulty of achieving this is demonstrated by the frequency with which our students express discomfort about being graded subjectively on scientific material. Our response is to strive to both make our expectations clearer to the students, and to explain to them that science involves subjective judgements. In this connection we agree with Bailey's recent comment that " we should not be afraid to use our professional judgement in assessing skills which do not lend themselves to objective measurement"[22]. Every year we find that a few students attempt to memorise the case studies, but the approach works very poorly because of the style of exam question that we set.

The material presented in the Case Studies in Concept Development could be used within any standard course in General Chemistry, to reveal to students how the concepts they are learning were developed, and traditional teaching approaches could be used. However, a major advantage to presenting new material in an inductive reasoning approach is that it greatly facilitates active learning approaches in the classroom, and we recommend this approach strongly. Lecturing about the development of concepts may well be more illuminating to the students than simply describing the details of a concept, but ultimately it probably only shifts the focus of the student from memorising the concept to memorising the experiments. Rather, the goal of a chemistry course, and thus the goal of classroom activity, should be to stimulate independent critical thinking about chemical concepts under the guided instruction of the teacher.

We have found over the past seven years that the combination of interactive teaching and concept development studies has been both effective and well received by our students. A significant question is whether the approach is only effective at a highly selective institution like Rice University. We cannot currently answer that question directly, since the approach has not been employed anywhere other than Rice. However, we do get a broad profile of student backgrounds, particularly with regard to prior instruction in Chemistry. Our surveys demonstrate that the approaches described in this paper are more frequently perceived to be effective by our more poorly prepared Chemistry students than they are by our well prepared students. These data suggest that the interactive and inductive learning approach should find wide applicability.

We conclude with a few anonymous testimonials from our students, submitted during the Fall 1999 exit survey. Whether these are truly representative of the opinions of most students is open to question. But these are powerful statements about the impact on at least these two students.

"I feel that I have really learned chemistry. The way that it is presented in the case studies book simply forces you to pay more attention to the subject matter and to have an in depth understanding of the chemical phenomenon."

"I will admit, that at the beginning of this course, I was one frustrated person who couldn't stand the case studies, but as time progressed, I found myself actually grasping to certain concepts and ideas that I never cared for in high school. You see, in high school, I was just given the theories and laws and their respected formulas to memorize, and that's exactly what I did. But in this course, I actually knew why those theories existed; why they carried those certain formulas; I couldn't memorize anymore; I really had to understand what was going on…and that has been the most important lesson of all."

Availability

The complete text of 'Case Studies in Chemistry' is available on-line to educators by permission of the author at http://chemed.rice.edu/CaseStudies. Both html and pdf formats are available. Case Study 3 can be accessed without registration. The rest of the text requires registration on-line with the author.

Acknowledgments

The author is grateful for the input, insight, and assistance of Dr. Susan D. Wiediger in preparing this manuscript and for the analysis results presented. This work was supported in part by grants from the Robert A. Welch Foundation of Houston, Texas, the Brown Foundation of Houston, Texas, and Rice University's Vice President for Information Technology.

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SolEq: Tools and tutorials for studying solution equilibria

PAPER

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SolEq (Solution Equilibria) is a CD-based package of tutorials designed for teaching equilibria to senior undergraduate students. Between them, they cover the principles and applications of acid-base, redox, solubility, and metal-ligand chemistry in both homogeneous and heterogeneous systems. It also provides the computational software for applying equilibrium principles to real systems (speciation programs, database, ionic strength and van't Hoff corrections *etc.*). The 29 tutorials and 8 computational packages are linked seamlessly *via* tool bar functions. SolEq has been used to support lecture and laboratory courses on environmental chemistry, coordination chemistry and analytical chemistry. It has also been used to create a customised refresher course for a graduate about to embark on a research programme in environmental chemistry.

Introduction

Equilibrium principles play a pivotal role in chemistry. For example, equilibrium processes are critical in the aquatic environment around us, and in the plasma and intracellular fluid within us. We recognise the importance of equilibrium by inclusion of topics such as solubility and acid-base theory in elementary chemistry courses, even though we may not cover them rigorously. However, these principles also underpin more complex systems and applications (*e.g.* environmental, industrial and biological processes, speciation and coordination chemistry).

In spite of the central role that this topic plays in chemistry, we were unable to locate suitable resources to support two undergraduate courses that we are required to teach. One is on 'the energetics of complex formation', an advanced inorganic chemistry course that involves an in-depth treatment of energetic (equilibrium) principles. The other is on aquatic chemistry, with emphasis on equilibrium reactions (metal ion speciation) and redox processes in environmental systems.

Our survey of available resources showed that excellent texts are available in specialist areas. Typically these adopt a chemical energetics (equilibrium) perspective against which to address issues in environmental chemistry[1,2], industrial chemistry[3], and aquatic chemistry[4]. These texts, because of their depth, rigour and specialisation, are not appropriate for courses to non-specialists or for a generic approach. In other areas, such as thermodynamic aspects of coordination chemistry and its applications in biological systems we have found a dearth of suitable teaching resources. We therefore determined to create a resource that would meet our requirements and be suitable for use by middle and advanced-level university undergraduates and by graduate students