CREATIVITY VS. STRUCTURE: A CHALLENGE IN DISCOVERY CHEMISTRY

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> *I would do away with introductory chemistry lectures completely and build a first year (chemistry) course entirely around experiments*
>
> Harry B. Gray
> ACS Priestley Medalist (1990)

Introduction

Traditionally in most institutions of higher education, chemistry is considered to be a very structured and vertical subject matter. In addition, practitioners of science have been preaching that creativity has been bestowed on only a few selected minds. Instruction is still characterized by a model in which the teacher discusses the material, tests the students on this material, and then turns to the next topic. To combat this situation, innovations and proposals soar, sweeping reforms are adopted, yet ultimately, most teachers return to textbook-based instruction, or the "talk-and-chalk" method.

During the last decade or so, hundreds of published studies and reports have come to the same conclusion: *The educational foundations of our society are presently being eroded by a rising tide of mediocrity that threatens our very future as a people.*

As chemists, we agree that the laboratory component is crucial and an essential part of the curriculum. However, in most situations we find that:

- there is little coordination between the laboratory and other aspects of the course;
- in a typical experiment, neither students nor their instructor have any doubts about the outcome; the only question unanswered is the extent of agreement between the students and the "correct answer";
- in the laboratory, the students "mimic" or go through the physical movements of various techniques without involving thinking skills;
- the curriculum is "a random assortment of arcane facts."

Since we teach the way in which we were taught, we should not be surprised that the faculty repeats the same process with their students. Effective science teaching has proven to center around laboratory experience where the students "discover" scientific concepts through experiments [1]. This curriculum reform using the discovery approach has been developed primarily for the future teachers, in which they become part of the process by participating first-hand in an investigation.

Science as the Process of Discovery

The constructivist theory [2-5] predicts that hands-on activities can play an important role in learning because students are actively involved in the process of constructing science. To be successful, the hands-on activities should be characterized by a process in which the students discover something about their daily life, rather than merely confirming or verifying something they read in a textbook; in other words, activities that more accurately reflect the process by which students can practice and develop critical thinking skills used by research chemists while constructing chemical knowledge.

The design of these activities, however, must avoid the trap into which so many traditional laboratory courses have fallen—a trap characterized by experiments that tell the students what they are expected to learn, and implemented in an environment in which students come to the lab, read the appropriate section of the lab manual, make a series of observations or collect experimental data, record these observations or data, and then go home.

Science is a creative endeavor and, therefore, it is important to remove as much as possible the "recipes" that often appear in general chemistry experiments. The experiments should provide information and guidelines rather than "recipes" or procedures as appropriate.

Because the goal of these activities is to actively engage students in the pursuit of deep understanding, to be successful they must be developed within a framework that permits a proper balance between a structured laboratory activity and opportunities for students' creativity. Our curriculum for the basic chemistry courses prepared for the future teachers recognizes the fact that our students are not familiar with this approach. Furthermore, the integration of content with pedagogy using the discovery method is an integral part of our teaching learning process.

The Project

Over about the last ten years, we have developed a project with grants from the National Science Foundation (Grant # DUE-9354432) and the U.S. Department of Education-MSEIP

(Grant #P120A30018). The instructional format utilizes hands-on activities and the discovery (inquiry) approach using locally available, low-cost materials and equipment, and integrates the content and the pedagogy. Instead of merely rearranging the order of presentation, adding new, presumably exciting topics, and eliminating subject matter that is deemed unnecessary or uninteresting, we decided to make the laboratory activity the centerpiece of the learning experience.

The laboratory-centered instruction utilizes experiences where the student discovers concepts which are designed to illustrate the experimental basis for science. These experiences do more than just introduce students to fundamental techniques and lab procedures; they also contain hypothesis formation, data gathering, analysis, and hypothesis testing stages. Concepts introduced through laboratory activities are then followed by classroom discussions building on the experimental nature of science.

The Motivation for Developing Discovery Labs

Several years ago, the Committee on Professional Training of the American Chemical Society (ACS) came to the following conclusions:

> The continued decline of student interest in science and mathematics is held by many to emanate from ills attributed to introductory courses. In chemistry, the introductory courses are often seen as needlessly dull and difficult, and more a barrier than an entrance to the subject.

Most institutions are not immune to this problem. Although overall enrollment in science courses is generally stable, only about 10% of science majors actually complete their chosen degree program. This can be understood by noting that introductory chemistry courses are required for all science and education majors, but almost 50% of the students in general chemistry either drop the course or receive grades of "D" or "F."

The students enrolled in general chemistry believe that the courses contain a series of abstract concepts for which they can find no applications outside of the classroom. A study of the faculty in the chemistry departments generally reveals that a great majority teach the way they have been taught: use traditional "talk-and-chalk" teaching styles, and use the laboratory to verify the concepts and principles covered in lectures.

After a quick study of the chemistry departments of most institutions in Puerto Rico, it was found that:

- the curriculum is traditional and taught in a classical manner; it relies heavily on lectures and textbooks to present material. The laboratory is being relegated to the role of verifying principles covered in lectures and, while this was an efficient way to cover concepts and facts, it didn't expose the student to the basic processes of chemistry;
- we must find a way to ensure a more active participation by every student.

We are convinced that the problems with the introductory courses cannot be solved by changing the order of presentation of topics, or by adding new, presumably more exciting topics. It requires a different perspective on teaching chemistry, in which **the laboratory should be the centerpiece of the students' learning experience;** whereby, concepts are introduced in the laboratory and then discussed after the laboratory activity is completed. This could only be achieved with an investigative approach, which involves the students in questioning, forming hypotheses, observing, testing, designing experiments, organizing and seeking patterns in data, developing qualitative and/or quantitative analysis of data, forming concepts, and communicating results in a scientific manner. In this approach, the instructor is no longer an authority figure who acts as the primary source, but as a guide in a situation where students discover concepts for themselves. In other words, the classroom should have a constructivist environment.

The Framework

The basis of all the laboratory activities is the learning cycle. In each activity, the students have an opportunity to explore, and possibly with the help of the instructor, discover the concept in the context of their daily life. Emphasis is placed on the nature of science, the context, and the applications of science.

The Curriculum

A series of student-tested laboratory activities have been developed for use in general chemistry courses. The experiments have the following characteristics:

- each experiment has a student manual and a teacher's guide;
- the students are given the information they need to carry out (and in some cases design) the experiment;

- they are given guided exposure to specific laboratory techniques and help to lead them to develop for themselves an understanding of significant chemical concepts;

- they are given questions for discussion that ask them to think about the analyses of the data and implications of the experiment they performed or the data they collected;

- a key objective is to learn how to approach a particular problem while gaining appreciation for the practical applications of chemistry. Relevant application questions are included as "Extensions and Applications."

The Philosophy of Discovery

The goals of these experiments are to achieve a balance between the process and content of chemistry, to show chemistry as it is done by practicing chemists, within an environment in which students build conceptual knowledge.

The experiments are not linked to a particular textbook, or even style of text. The goal in developing these experiments is to link many instances, one laboratory experience to another. However, sufficient guided inquiry directives within every experiment for both safe and successful learning outcomes are provided. In this sense, the user can perform selected individual experiments in any order.

The nature of the discovery approach to chemistry might be best understood by examining the following series of experiments that begins with the discovery of differences between “copper” pennies minted before or after 1982. These provide the basis for discussions of stoichiometry and limiting reagents, builds a quantitative model of the relative activity of the different metals, and then uses the chemistry of these elements to introduce both corrosion and chemical kinetics. Each experiment starts with a question stated in a practical context. Examples are:

- Are All Pennies the Same?

- How Much is Enough?

- How Much is Too Much?

- Using Metals to Make Electricity.

- Which Metal is More Active?

- Why is a "Harley" Chrome Plated?
- Why Did My Watch Stop Suddenly?

The Format of Discovery Labs

To sustain interest and foster curiosity, the student manual for these modules contains only the basic information needed to do the activity: an introduction, objectives, list of materials and procedures, explicit safety directives, observations, data analysis. This information guides the students through the process of organizing the data in a manner that is logical to them in the stages of hypothesis formation and hypothesis testing, and results and conditions.

The teacher's guide is also a central feature of each experiment and contains the following sections: a detailed introduction, concepts developed through the experiments, skills used, materials and chemicals needed, safety, anticipated results and comments, extensions, and global time.

The experiments are designed in the spirit of team learning and collegiality to maximize the contributions peers can make in improving learning and chemical understanding. Ten topic units which are common to most general chemistry courses have been developed. Examples are: scientific method, stoichiometry, gases, and oxidation reduction. Each unit contains two to three experiments with the characteristics described earlier.

The Approach

A curriculum reform through laboratory-driven instruction has been designed and developed for the teacher preparation program in order to give students a feeling of the reality of science by an encounter with phenomena. Regardless of the exact nature of the program, it is necessary to find a proper balance between a structured laboratory environment and opportunities for student learning and creativity.

The laboratory is used inductively—to introduce concepts, which are further developed in post-lab discussions. This is achieved through an investigative approach, which actively involves the students. In this process, the instructor acts as a facilitator who assists in the process in which the students discover concepts for themselves. In other words, the laboratory provides a constructivist environment.

The key feature of the laboratory-driven courses is the discussion that occurs when student-generated data are combined. This can be facilitated through the use of a low-cost computer interface which pools student data and projects these data on a television monitor [6].

Students create knowledge from experimental evidence in a post-lab discussion session. The role of the instructor is important in this process; for example, by suggesting graphical analysis or another experiment, thus breaking complex questions into a series of simpler steps and allowing student creativity to match their level of sophistication. In the discovery curriculum, the instructor remains a central figure, guiding and choreographing the activity.

The nature of the curriculum materials developed might best be understood through the following example.

Sample Experiment: How Long Can a Bubble Last?

A typical experiment begins with a question. The objectives include an investigation in a scientific manner by studying the effect of varying conditions (soap concentration, its temperature, bubble size) on the time that a bubble lasts [7,8]. Further, students are asked to design an experiment for determining the effect of different surfaces on bubble longevity.

The Effect of Concentration

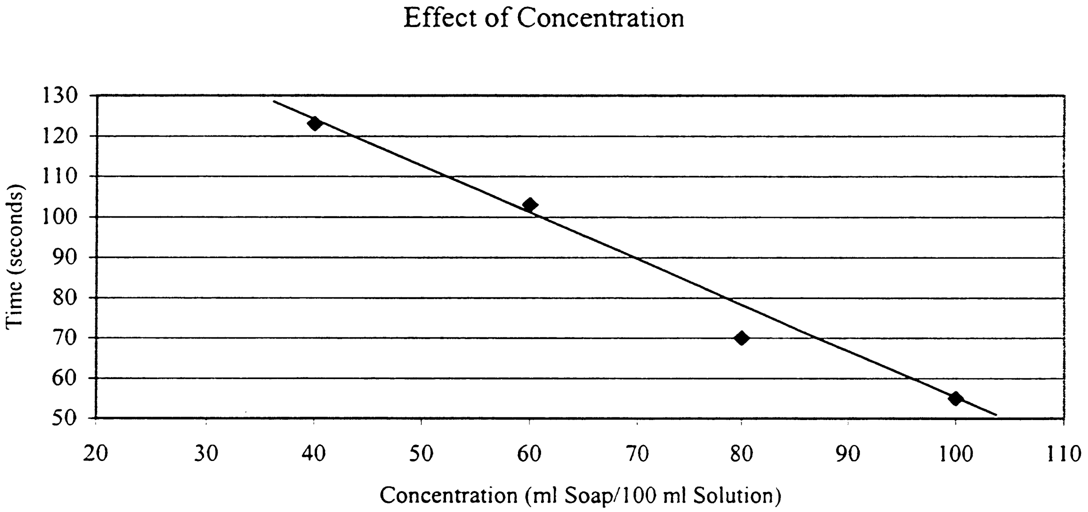
Students are provided with four soap solutions of different concentrations and asked to practice with one of the solutions to blow bubbles. They are asked to predict what should happen to the lifetime of the bubble as the concentration of the soap is increased. (Most students predict that as the concentration of the soap solution increases, the time taken for the bubble to burst [its lifetime] also increases.)

Then, instructions call for blowing bubbles of a known diameter on a flat laboratory surface using 1 ml of a liquid soap solution (Dawn® works best in our experience). They work in groups of two and record the instant the bubble bursts. They repeat their observations with all four concentrations until they get consistent results.

Each group collects its data and then all data are displayed for discussion. Each group's prediction is compared with the class data:

Concentration (ml soap/100ml solution)	40	60	80	100
Average time(s)	123	103	70	55

As part of the objectives, the students are asked to present data as a graph of the time of bubble bursting vs. concentration of the soap solution.



The teacher leads the discussion as to why their prediction and their observations contradict. Factors on which the lifetime of the bubble depends, such as hydrogen bonding, cohesive and adhesive forces, are brought in through their discussion and observations.

The Effect of Temperature

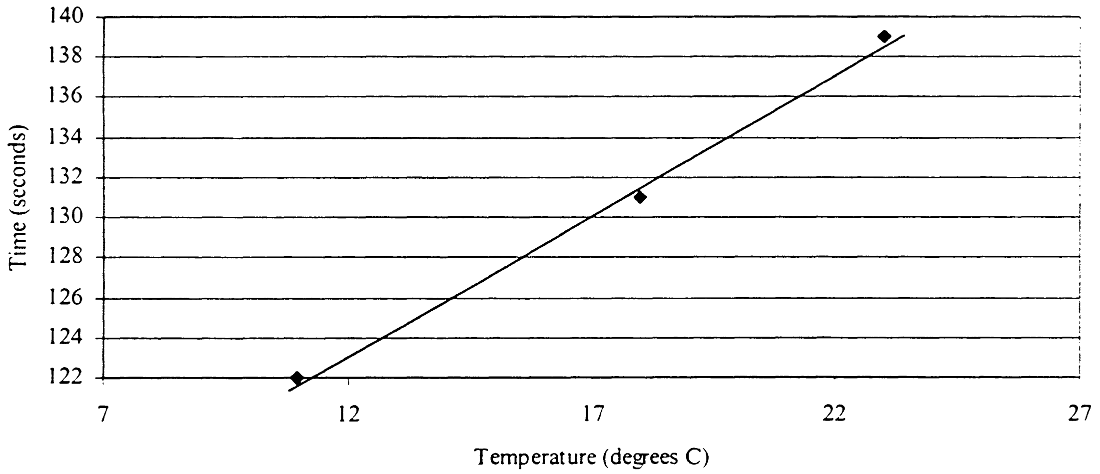
The students are asked to hypothesize what will happen to the lifetime of a bubble as the temperature varies. (Invariably, they hypothesize that as the temperature increases, the lifetime of the bubble decreases.)

They are divided into groups and make their observations at three different temperatures such as, 10°C, 20°C and 25°C. That is, one group of students perform the experiment at 10°C, the other at 25 °C, and so on.

The students are asked to provide their own data table and plot a graph of the time of bubble bursting vs. temperature of the soap solution for a specific size of the bubble. Again, their observations are not consistent with their hypotheses. The class data are again displayed.

Temperature (°C)	11	18	23
Average Time (s)	122	131	139

Effect of Temperature



Finally, the students are asked to design an experiment(s) to study the "effect of the size of the bubble," and the "effect of different surfaces" on the lifetime of the bubble. In each part, in the results and conclusion section, they are asked to summarize their findings and give a possible explanation for the problem under investigation. Through this activity, concepts that the students discover are: adhesion, cohesion, the wetting of a solid surface by a liquid and factors affecting reaction rates. Hydrogen bonding is reinforced and discussed further.

Evaluation

Preliminary evaluation of these experiments at several institutions (University of Puerto Rico at Cayey, Inter American University of Puerto Rico and Purdue University, W. Lafayette) suggests that we have met our goal of transforming the traditional laboratory experience into one in which some of the motivation for learning has been shifted from the instructor to the students. Qualitative data was gathered with Reflective Diaries and interviews with students; and, quantitative measures included a comparison of the grades obtained by students taking this course in the traditional and the discovery approaches. Students loved the approach, felt they were learning relevant chemistry and recommended this course to other fellow students. The chi-square comparison of traditional and discovery formats consistently revealed a higher percentage of "B"s and "C"s in the discovery format and a lower percentage of dropouts and "F"s. In our curriculum, students take an active role in the planning and carrying out of the activities, with emphasis on the processes, and not solely on the products of science.

Conclusion

The discovery-based curriculum developed inculcates student learning using easily accessible materials available in their daily lives through direct experiences. During the process, students make their own observations, acquire their own data, and analyze and interpret their data with guidance from the instructor and in collaboration with their peers. Although our model is not completely open-ended, there are sufficient elements of creativity in this structured format to support the insights expected of the students in the process of discovery. Throughout the process, the instructor is behind the scenes, a guiding force, choreographing the activity, ensuring that student creativity is called for in small, manageable increments.

We have developed reform of a general chemistry course by addressing the pedagogical needs of the teacher preparation program. This reform has synchronization in its philosophy and style of teaching. Our approach to pedagogy at the college level reflects the style of instruction that is expected of teachers in school, since the laboratory-driven introductory course mirrors many aspects of instruction that future teachers are expected to employ. ■

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