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Laboratories and Demonstrations

What Happens When Discovery Laboratories Are Integrated into the Curriculum at a Large Research University?

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The instructor is no longer an authority figure, who acts as the primary source of information, but a facilitator….

Traditional laboratories are often based on the hidden assumptions that students can, and indeed should, work alone, and that they can leave the laboratory when they have finished collecting the data or observations. Discovery laboratories provide an alternative to traditional laboratories in which one or more routes are taken by groups of students working toward the discovery of a specific scientific relationship or concept. The discovery laboratories used in this study were developed by colleagues from institutions where faculty teach the laboratory component of the course. The goal of this study was to see what happens when discovery laboratories are integrated into the general

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chemistry curriculum at a large research university where teaching assistants are in charge of the laboratory sections.

For the purpose of this study, we differentiated between a minimal level of success, in which discovery laboratories become an alternative approach to traditional experiments, and a significant level of success, in which they become a preferred approach. Evidence is presented to support the notion that discovery laboratories can be successfully integrated into the curriculum at a large research university, that students in the discovery laboratories believe they had to take responsibility for what happened in the laboratory, that both teaching assistants and the students reacted positively to the discovery laboratories, and that we achieved at least our definition of the minimal level of success.

Introduction

The laboratory experience is such an important component of the training of both scientists and nonscientists that a rationale is not needed for its inclusion. The opposite, in fact, is true—one would have to provide a rigorous rationale for its exclusion from the curriculum. Thus, it is not surprising that an enormous amount of time and effort are devoted to the laboratory, both to develop new laboratory activities and to shepherd students through the laboratory experience. It is, therefore, disconcerting to note that research has questioned the effectiveness of the laboratory experience [1–3], and laboratory work has been described as aimless, trivial, badly planned, and implemented without proper regard for its pedagogical and epistemological roles [4].

Imagine, for the moment, that you are a typical student enrolled in a chemistry course in which you are asked to do an experiment designed to measure the molecular weight of something that your instructor describes as a “volatile liquid.” You are told to weigh an empty flask, add some of the liquid to the flask, immerse the flask in boiling water, heat the flask until the last drop of liquid evaporates, remove the flask from the boiling water bath, allow it to cool to room temperature, and weigh the flask and the liquid that condenses in the flask. You are then supposed to pour this liquid into a waste container, fill the flask with water, and weigh the flask filled with water.

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Suppose that you then turn to the introduction to the experiment, which notes that this experiment involves the ideal gas law.

$$PV = nRT$$

It then states that the number of moles of gas in the flask when the last drop of the volatile liquid evaporates is equal to the number of grams of this gas divided by its molecular weight.

$$PV = \left(\frac{g}{\mathrm{MW}}\right)RT$$

and concludes that the molecular weight of the volatile liquid can be calculated as follows.[1]

$$\mathrm{MW} = \frac{gRT}{PV}$$

What hidden signals would this approach to the teaching and learning of science send to you and your fellow students? First, and foremost, it sends a clear signal that you do not have to understand the procedure for doing the experiment. You do not have to understand why the amount of the volatile liquid added to the flask is not important; why it is important to use a Dumas flask that has a very narrow opening at the top through which air can escape; why it is important to stop at the exact moment that the last liquid disappears; why it is important to know the boiling point of water, but not the boiling point of the volatile liquid; or even what the term *volatile* means when it modifies *liquid* in this experiment.

This approach sends a hidden signal that neither the author of the experiment nor the instructor in charge of the course believes that students can discover the following for themselves.

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[1] This approach to the Dumas flask experiment was repeatedly found during an analysis of more than a hundred custom-published laboratory manuals printed by the Burgess-Bellweather Publishing Company.

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- That the process of boiling the volatile liquid inevitably drives the air out of the flask.
- When the last drop of the volatile liquid disappears, the flask is filled with the corresponding gas at atmospheric pressure and the boiling point of water.
- Measurements of the volume of the flask, atmospheric pressure, and the boiling point of water can be combined to determine the number of moles of gas in the flask.
- Dividing the mass of the liquid that just fills the flask when it evaporates by the number of moles of gas in the flask at this moment gives the molecular weight of this substance.

Finally, this approach sends the hidden signal that the creative process that characterizes what scientists do when they “do science” can only be practiced by a minuscule fraction of the population. The vast majority of the students who pass through science courses must be content with routine exercises in which they follow in the footsteps of individuals with whom they cannot hope to compare themselves.

This raises the question: How did the Dumas-flask experiment outlined above evolve? Some would argue that this approach to the laboratory is a pragmatic reflection of the ability of the students they teach. They note that when the discussion of how the data should be analyzed is left out of the introduction to the experiment, the students cannot do the analysis on their own. They may be right, but our work suggests that they are only right when the experiment is done in an environment characterized by two hidden assumptions: first, that the students must work alone and second, that the students can (and should) leave the laboratory when they have finished collecting their data. Our experience at Inter American University in Puerto Rico and at Purdue University has shown that students can construct the relationship between the data collected in an experiment and the conclusions we want them to reach when they are involved in the design of the procedure used to collect the data, when they are encouraged to work together, and when the class as a whole discusses the experimental results.

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Origin of the Discovery Labs

In 1990, members of the chemistry faculty at Inter American University in Puerto Rico became involved in a project that demonstrated the value of a hands-on, activity-oriented approach to teaching science to elementary students. This experience led them to reflect on the difference between what they found successful when working with young children and the routine classroom practices that characterized the undergraduate experience in chemistry at their institution, in which the curriculum relied on lecture and textbooks to present material and the laboratory was relegated to the role of verifying principles covered in lecture.

They decided, therefore, to take a different perspective to teaching chemistry; one in which *the laboratory became the centerpiece of the students' learning experience*. This involved significant changes in the roles of both the students and their instructor. On the basis of their observations or data, students are now expected to form and test hypotheses that inevitably lead to the discovery of concepts, which are then discussed in class. The instructor is no longer an authority figure, who acts as the primary source of information, but a facilitator, who assists in a process in which the students discover concepts for themselves.

In many ways, this laboratory-driven curriculum represents a return to the perspective proposed in 1903 by Armstrong, who argued that the laboratory should be a place for *doing in order to understand*; a place where students discover information that others could only acquire by rote memorization [5]. The laboratory-driven curriculum also represents a closer fit to the intentions of the laboratory program developed at the University of Giessen by Justig Liebig, which was the model on which the teaching laboratory was built. In Liebig's laboratory, once basic skills were mastered, "Everyone was obliged to follow his own course. In the association and constant intercourse with each other, and by participating in the work of all, everyone learned from the others" [6].

What is a Discovery Lab?

Knowledge developed in the laboratory, like knowledge developed elsewhere, is constructed in the mind of the learner [7–9]. In order for learning to occur, knowledge must be seen as a viable and useful alternative to not knowing at all and to previously held ideas [10, 11]. With this premise in mind, we have developed a series of discovery-based laboratory experiments for use in general chemistry [12] that have the following characteristics.

- Each discovery laboratory centers on a single concept or question.
- The students are given the information they need to design and carry out the experiment, but only this information.
- They are given questions *for discussion during the laboratory* that ask them to reflect on the implications of the experiment they perform or the data they collect.
- Small groups of students work on collecting data for different aspects of the experiment.
- The data collected by the individual groups are pooled and then discussed by the class as a whole.
- For many experiments, more time is devoted to discussion of the data than for the collection of the data.

A variety of terms such as *inquiry, discovery, replication,* and *verification* have been used to portray different goals and formats for laboratory experiences. We use the term *discovery laboratory* to mean a sequence of events designed by the students under the guidance of a teacher in which students construct meaningful knowledge about phenomena in a laboratory setting. Discovery laboratories are characterized by three necessary components.

- The teacher must have a clear understanding of the phenomena to be observed prior to the laboratory experience while the students should not.
- The students should be actively involved in developing or deciding upon at least some elements of the procedures of the laboratory exercise.
- The students should have opportunities to encounter both positive and negative results. If the students only observe results that agree with their expectations, the exercise becomes one of replication. If they only obtain results that conflict with their predictions, construction of useful, viable, meaningful knowledge becomes difficult, if not impossible.

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Because students are involved in decisions about how the experiment is performed, discovery laboratories have more than one route to a successful conclusion. This characteristic provides a way of distinguishing between our notion of a discovery laboratory and what we would consider an inquiry laboratory. An *inquiry laboratory* has both different potential procedures and different potential learning outcomes. Although a discovery laboratory has different procedures, it has a single common learning outcome. In a *discovery laboratory*, there is a specific scientific relationship or concept that the students will discover.

Discovery laboratories build on the POE—predict, observe, explain—technique proposed by Gunstone and Champagne [13], in which students are asked to predict the outcome of some event, justify their prediction, describe what they see happen, and then reconcile any conflict between what they predict and what they observe. White and Gunstone [14] argue that the situation in which the POE technique is used must be one for which the students feel qualified to make a prediction based on personal reasoning. Gunstone and Champagne suggest that it should be used under conditions where many of the students predictions are supported by their observations (what we have called positive results). But, it should also be used under conditions where the students' observations are not supported by results.

Consider, for example, one of our discovery laboratories, which builds on the students' prior experience with the reaction between aluminum, magnesium, or zinc metal and hydrochloric acid. The laboratory begins by asking the students to predict the relationship between the volume of H_2 gas produced by this reaction and the size of the metal sample. (They predict a straight line that could be extrapolated more or less indefinitely.)

Each group of students measures the volume of H_2 gas generated by a series of four metal samples of different size. When individual groups plot their data, they find that three of the four points fit on a straight line and they are seldom concerned about the fact that one of the data points does not. When data for the various groups in a laboratory section are pooled, however, the students find that it is always the data point for the largest metal sample that does not fall on the straight line, as shown in Figure 1. They inevitably conclude that there is a point beyond which increasing the size of the metal sample does not lead to an increase in the volume of hydrogen gas. By reconciling their predictions and observations, the students doing this experiment are

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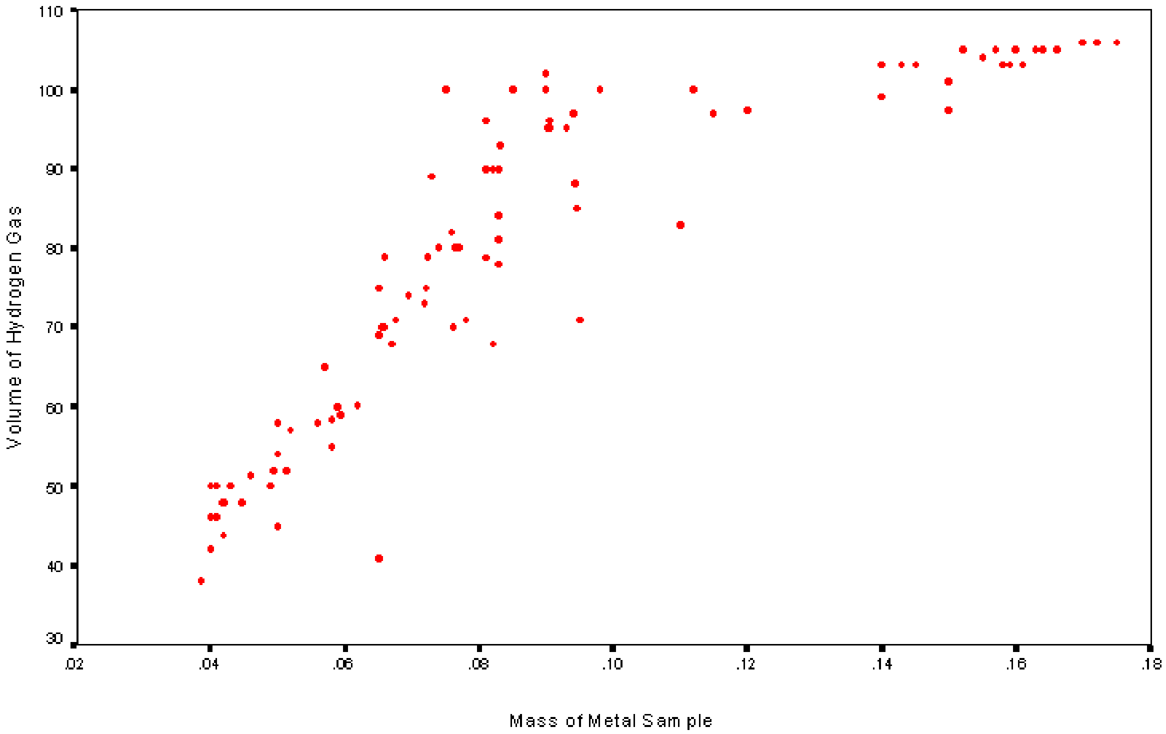

FIGURE 1. A COMBINED PLOT OF THE VOLUME OF HYDROGEN GAS VERSUS THE MASS OF MAGNESIUM RIBBON FOR THREE SECTIONS OF 24 STUDENTS WORKING IN GROUPS OF THREE WHO RAN FOUR METAL SAMPLES PER GROUP.

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led to the discovery of the concept of limiting reagents on the basis of a laboratory experiment in which the term *limiting reagent* never appears.

Discovery laboratories have been developed at a variety of institutions [15, 16]. The laboratories used in this study were written by one of the researchers and colleagues from around North America [12]. Prior to implementation in this study the laboratories had been used for two years at Inter American University in Puerto Rico where faculty teach the laboratory component of the course. Only minor changes were made in the laboratories prior to this study to accommodate equipment available at Purdue and the constraints of a three-hour laboratory period. The goal of this study was to see what happens when discovery laboratories are integrated into the curriculum at a large research university where teaching assistants are in charge of the laboratory sections.

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Implementation

The attempt to implement a series of discovery laboratories into a large section of first-year chemistry students constituted a complex task. Not only were there logistical considerations, such as forming student groups and organizing the prep-lab staff, there was also the greater challenge of implementing these experiments with a teaching staff made up of novice teaching assistants who had to understand the concept of constructing knowledge on both a philosophical and a personal level.

At the first staff meeting, the theoretical and philosophical framework for the discovery laboratories was outlined for the teaching assistants who would be implementing the laboratories. In order to clarify the notion of the construction of knowledge, the teaching assistants were asked to differentiate between hearing information, understanding ideas, and actually using knowledge. The importance of allowing students to struggle with a concept was stressed, with emphasis on how to provide students with enough information to work out the point of the exercise without giving them so much that they no longer need to work it out for themselves. As constructivists, the authors recognized the importance of spending time during each subsequent staff meeting discussing both successes in and frustrations with the implementation of the previous week’s experiment as well as suggestions for how to approach the next week’s laboratory. Throughout the semester we encouraged—and received—both negative and positive feedback from the teaching assistants.

The Course

Chemistry 115 is the first half of a two-semester sequence taken by science and engineering majors at Purdue. Approximately 2000 students enroll in the course each Fall and they are randomly divided into five large lecture sections, which are subdivided into groups of 24 students who meet with the same teaching assistant for both laboratory and recitation sessions. Two faculty are assigned to the two lecture sections that include a Monday afternoon lecture (115M) and two faculty are assigned to the two lecture sections that include a Tuesday morning lecture (115T). The faculty in 115M and 115T split the course vertically, teaching both lecture sections for either the first half or second half of the semester. The discovery laboratories were implemented in the fifth lecture section (115A), which is taught by the same faculty member all semester.

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There were no common elements among the three sections of this course (115M, 115T, and 115A); thus, it was impossible to collect experimental versus control data that would allow us to compare students using the discovery laboratories in 115A with those in the other sections using more traditional experiments. We chose, instead, to use an Action Research methodology [17, 18] in which all of the students in 115A were exposed to the intervention.

Roughly 60% of the grade in the discovery-laboratory section was based upon four multiple-choice exams. Slightly more than 10% was based on a series of ten short-answer quizzes. Formal group laboratory reports based on the 11 discovery laboratories represented slightly less than 30% of the total course grade.

Students

The students enrolled in Chemistry 115A during this study were a typical group of first-year science and engineering students. Almost all were in their first semester at Purdue and virtually all had taken high school chemistry.

The students were organized into groups of three for the discovery-laboratory sessions. Rather than using ability or motivational level as the criterion for group formation [19, 20], the groups were formed on the basis of proximity of living arrangements to facilitate meetings outside of class time when the students got together to discuss and write reports. (The decision to group students on the basis of where they lived is the result of almost 20 years of experience with group work in general chemistry laboratories at Purdue University.)

Teaching Assistants

Eleven teaching assistants were assigned to CHEM 115A, ten of whom taught two sections of 24 students and one who taught one section. TAs were assigned to CHEM 115A by matching their course schedules with the times at which CHEM 115A was taught. Ten of the TAs were first-year graduate students at Purdue; nine had little or no college teaching experience.

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The Role of the Authors in this Study

The first author was the instructor responsible for teaching the large lecture section in which implementation of the discovery laboratories occurred; the second author was the course supervisor responsible for ensuring that course policies were implemented by the teaching assistants. Both are devoted constructivists. Both also value group deliberation as a vital part of the progress of science. We recognize that our positions within the course, coupled with our enthusiasm for group work, are possible sources of bias in the collection and analysis of data, perhaps giving rise to a more rosy picture of the classroom environment than was warranted. But, our enthusiasm and positions of power within the course also had the advantage that we could immediately make changes to resolve problems brought to our attention by students or teaching assistants. Furthermore, both the students and the teaching assistants might have been more willing to talk about their concerns because they were active participants in the experiment. Perhaps the best evidence that the advantages of our positions in the course outweighed their disadvantages is the extent of agreement between the results of anonymous surveys and personal interviews.

The Study

This study addressed the following research questions.

- Can discovery laboratories be integrated successfully into the chemistry curriculum at a large research university?
- What are students’ reactions to the discovery laboratories?
- What effect, if any, does participating in the discovery laboratories have on student learning of chemistry?

The theoretical framework for this study falls within the domain of hermeneutics [21]. Our goal was to understand what the students thought of the discovery-laboratory program and learned from this program in order to understand what is necessary for successful implementation of these laboratories and to convey this information to a wider audience. The study is hermeneutic in the sense that we are trying to give students the opportunity to be heard, to have a “voice,” through interpretations of the meanings of their statements and actions. If successful, this study should allow the reader to develop an appreciation of what occurs during a discovery-laboratory experience—from the students' perspective—and to understand what the students learned from this experience.

Methodology and Data Collection

Because one of the main goals of this project was to find out what students were actually learning during the sequence of laboratory experiences, it was necessary for the researchers to spend time in the laboratory with the students and teaching assistants. Each week the course supervisor circulated through the ten laboratories, talking to students and their teaching assistants. The course instructor would talk to students and teaching assistants about the laboratory program during and after class as well as when appointments were arranged during office hours. The purpose of this contact was to ascertain the extent of student understanding and satisfaction with the course, in general, and with the discovery-laboratory program, specifically.

To determine if the discovery laboratories had been implemented successfully, it was necessary to define what would constitute success. For the purpose of this study, we defined a minimal level of success as a classroom environment in which the students feel as positive about chemistry and understand as much chemistry as those who were not exposed to the discovery laboratories. A significant level of success was defined as a classroom environment in which the students achieved a better understanding of chemistry and/or were more favorably disposed to chemistry as a result of their experiences in the discovery labs. If the first level of success is achieved, the discovery laboratories become an alternative approach to traditional experiments. If the second level is achieved, discovery laboratories become a preferred approach.

Six sources of data were used in this study: (1) field notes collected while circulating through the laboratories, (2) staff-meeting notes, (3) transcripts of audio-taped interviews with students, (4) transcripts of audio-taped interviews with teaching assistants, (5) a Likert-scale survey of student attitudes, and (6) the student's grades in the subsequent course in chemistry (CHEM 116). Each source of data was applied to answering research questions for which it was appropriate, thereby maximizing the reliability of our conclusions through triangulation of research techniques.

Results and Discussion

Our results can be organized around a series of assertions that address the issues raised by the research questions that drove this study.

1. Discovery laboratories can be integrated successfully into the chemistry curriculum at a large research university.

Although occasionally frustrated by situations that arose, both the teaching assistants and the students were content with the roles in the laboratory experiences they were asked to accept. In staff meetings the discussion occasionally focused on the teaching assistants' feelings of frustration caused by problems they had with implementation of the discovery-laboratory approach, or on the bleakness of the students' understanding, but these meetings almost always ended in a "conspiratorial tone," in which the TAs focused their attention on decisions about how we could approach the teaching of the next concept in a discovery mode.

As the semester progressed, the discovery process became more integrated into the manner in which the laboratory experience was implemented. We spent more time in staff meeting talking about the concepts to be discovered and the format for laboratory reports and less time justifying the discovery method. As can be seen in the following dialog among the teaching assistants and the course supervisor, more time was also spent identifying topics that would be difficult for the students and developing strategies to resolve these difficulties.

> Kathy: I think that they will have a hard time knowing how to begin. Two weeks ago they got stuck looking for a reaction when the metal was placed in its own solution. How are they going to know that they need to worry about water vapor pressure in the flask? There is no evidence in the reaction that their volume values are not only hydrogen. We will have to tell them that up front.
>
> Steve: We could let them proceed and in recitation go over the results and then point out the discrepancy and then they could adjust for the water vapor and redo their calculations.
>
> Kathy: They are not going to be very happy if they have to do the calculations twice because we did not explain water vapor pressure to them. It will only take five minutes to explain the concept.
>
> Sandra: How do you explain water vapor pressure in five minutes?

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> Supervisor: They understand that puddles evaporate, and if you point out that the water is escaping out of the puddle with some force then they may begin to understand that it escapes out of the beaker and into the flask with the hydrogen in it.
>
> Sandra: It took me hours to learn how to calculate it.
>
> Steve: Maybe we could give his [the course supervisor's] five-minute explanation as part of pre-lab and give them the water temperature and tell them to read about it and incorporate it into the calculation of the amount of hydrogen. Then in recitation we can go over the discrepancies between those that were able to work out the calculations and those that couldn't.

The teaching assistants were initially skeptical about the prospects of achieving a satisfactory understanding, but together they were able to come up with a working solution that was consistent with the philosophy of the discovery laboratories and their concerns about the lack of student comprehension of a complex chemical system. They agreed upon a plan containing just enough information to let the students figure out a solution, without giving the solution to the students.

In private discussions, certain teaching assistants lamented their occasional disbelief in the success of the program. Disbelief surfaced most often when the teaching assistants were frustrated with recent experience. On the basis of his early experiences, Jim expressed concern about whether his students had enough knowledge to make connections between concepts.

> Jim: I don't know if they are learning what they should be. I want to tell them "this is what you need to know, this is what you need to do." Sometimes I think they are never going to get it if we don't make it more obvious. And another thing, it is so difficult for them to get good results, and so they are trying to make interpretations from bad results and then how are they supposed to find out what they need to know?
>
> Supervisor: This comes back to how we think they learn. In theory if we just tell them the answer we think that they will not truly understand it, and that they will not retain it.
>
> Jim: I, kind of, know what you mean, but we are under a lot of pressure to get to the end of the lab and to get done. I don't know how we are supposed to do it all.

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Jim was not alone; Sandra, Kathy, and Steve also experienced frustration and tension with the implementation of the discovery laboratories, but all four were able to resolve these issues in a manner consistent with the philosophy of the program.

When we visited the laboratories, the researchers were often pleased with what we observed in terms of the discovery process. Yolanda and Jim, for example, described what generally occurred during their labs as follows.

> Yolanda: At the beginning I try to tell them what they need to know to get started, and what things they need to be careful about, and what they need pass in. But I don't tell them everything. I always tell them that after they get started they will have to make some decisions, or have to interpret that data here, or something like that. I don't give it all to them. And I tell them if there is a difficult piece of equipment to handle. Like you said, "They have to figure it out."
>
> Jim: I try to do it like Yolanda, but I always take the outline and put it on the board and make notes about what has to happen at each step. Then as we go through the lab I make them tell me what data they need. But I don't let them ask me about why they need the data. I try to make them think about it themselves.

Yolanda and Jim tried to make the students actively participate in decisions regarding laboratory procedure and not let the students fall into the trap of gathering data they did not comprehend; both examples of teaching behavior consistent with the philosophy of the discovery-laboratory process.

At times, the researchers were disappointed by what they saw when they visited the laboratory. On more than one occasion, a teaching assistant would be standing at the front describing a detailed list of the things that needed to be passed in, or telling the students, "do this [technique] followed by this [another technique] and this [still another technique] and this [yet another technique]." These teaching assistants were valiantly trying to give the students a long and useful list, but the students' blank looks and vague stares suggested that they did not know what the teaching assistant was talking about. When discussing a similar sequence in which he was involved, one of the teaching assistants expressed his need to conform to the pressure of the situation as follows.

> Bob: I was telling them all the things they needed to do in order to complete the report. Just like we said in our meeting, I want to be sure they know before

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> hand what we expect, how you are going to grade them. That way it is fair. I don't want them to come back to me and say "why didn't you tell me we had to do things this way in the first place?" This way I give it to them in steps that are easy for them to follow and they don't have so many problems getting it done and they know where they have to go.

Bob was conscientiously working to minimize the problems students would have by providing them with information they would need, but he seemed to be unaware of the almost total lack of receptivity of his students to the information he was giving.

Situations such as Bob's were not isolated incidents, but neither were they normal teaching behavior. The typical implementation of most discovery laboratories by most teaching assistants involved providing just enough information to get the students started, but not more than the teaching assistants felt the students could understand at any time. While the teaching assistants may have made mistakes, they generally seemed to be trying to implement the laboratory experiences as the authors and course supervisors intended.

The answer to the first of our research questions is therefore: Yes. The students made it through the semester; the instructors, teaching assistants, prep-lab staff, and the university survived intact the implementation of eleven discovery laboratories in the course. At least at some minimal level the laboratories were implemented successfully by teaching assistants who appeared to be trying to teach in a manner consistent with the philosophical basis for the discovery laboratories.

2. In general, students believed they had to take responsibility for what happened in the laboratory.

To find out whether the students perceived the need to make decisions in the laboratory and/or to discover some of the concepts themselves, we asked them to tell us what occurred in the laboratory and to describe their roles in deciding what happened during laboratory time. Some students felt that they did not have to do much decision making.

> Tim: in lab he [the teaching assistant] would start the lab and explain what we were supposed to do and then told us just do it, walk around if we had problems, be there to answer...

> Supervisor: How much of what you did in the lab do you think you had to determine yourself? How much flexibility do you think you had?

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> Tim: I don't think there was really much flexibility at all. It was all written out for us and we basically followed it, there wasn't really anything we could do different, really.

Other teaching assistants, however, clearly passed responsibility for analysis back to the students.

> Supervisor: Can you give me a snapshot of what your teaching assistant would do in lab?
>
> Mike: As far as lab goes, she pretty much left us to our own on that and I think that was a good thing cause it was a little more challenging for us. She would help us where we needed help but if we were trying to get a question out of her for one of the answers she'd say, "Look at your results, figure it out for yourself."
>
> Supervisor: Can you describe the amount of responsibility you were given…to carry out the lab?
>
> Mike: I think we were given a lot of responsibility, mainly when we walked into the lab she told us what kinds of things we would have to include in our lab notebook, but then just to go ahead and do it. I guess for the first couple of labs it took a little getting used to. I was used to getting spoon-fed.

The challenge of giving the appropriate amount of responsibility to students was echoed time and time again in the staff meeting discussions. The teaching assistants frequently lamented the challenge of balancing the need to finish a procedure, and get useful data with the desire to let students work things out on their own. As Sandra put it, "I understand the point of making the students learn the material themselves, but if we spend this much time struggling to collect gas here and waiting for other groups to finish, then we will never get to the endpoint of seeing that one reagent is limiting the reaction."

In addition to differences from section to section in the amount of responsibility the students were expected to carry, analysis of students' reaction to the discovery laboratories was also complicated by differences in their perception of what is a reasonable amount of responsibility for them to carry.

3. In general, students reactions to the discovery laboratories were positive.
We asked the students to predict what might have happened to their understanding of chemistry and their grade in the course if they had not been part of a discovery group.

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Some students indicated that although their grade might have been the same without the discovery laboratories, their understanding of course material probably would have been lower. Edith, for example, responded as follows.

> Edith: I can't say what I might have done, but I put a lot of time into chemistry and in my labs I did a lot. I think my grade is probably the same. My understanding, lately these past chapters, it took me a while to get into what he [the professor] wanted. My understanding is getting better. It was tough for me to understand in lecture.

Tip gave whole-hearted support to the idea of the group laboratories being beneficial.

> Tip: I think it [my grade/my understanding] would have been significantly lower. In any given lab there may have been one part that I understood really well, but I didn't understand another part. It may have been vice versa with my partners."

Perhaps the best evidence for a positive attitude towards chemistry from students who were enrolled in the discovery-laboratories section can be found in student's answers to the question of whether they would recommend enrolling in a section of CHEM 115 in which students worked together in groups. The end-of-the-semester student surveys indicated that 86% of the students who used the discovery laboratories would recommend or strongly recommend this approach. The same level of support was found for the suggestion that later courses in chemistry should use a group discovery-laboratory approach, and 74% either agreed or strongly agreed with the suggestion that working in groups in the laboratory had helped them understand course material.

Similar results were obtained during student interviews. Most of these students replied both rapidly and affirmatively when asked whether they would prefer taking another course in this format or whether they would recommend this approach to another student. They were invariably surprised that we would even ask this question. Similar results from interviews about their experiences in general chemistry were also obtained from students at the end of CHEM 116 during the second year in which the discovery laboratories were implemented.

4. Participating in the discovery laboratories may have an effect on student learning. There are many ways of measuring student success in any sequence of course work: the grade received in the course in which they are enrolled, the grades received in subsequent courses in that field, the students' ability to use the concepts they learn in

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TABLE 1. Assignments of Percentage of students earning letter grades in CHEM 116.

	A	B	C	D	F
Discovery-laboratory students	13.3	28.5	39.9	11.4	7.0
Non-discovery-laboratory students	18.1	29.2	32.4	15.0	5.3

other courses, and so on. In this case, the only available measure of success was the students' performance in the subsequent course, CHEM 116, which is shown in Table 1.

In general, the proportion of discovery-laboratory students receiving either an A or a D in CHEM 116 was lower than their cohorts who had not been part of the discovery-laboratory project and the percentage receiving a C was higher. On a five-point scale, the average grade for the discovery laboratory students would be 3.30, whereas the non-discovery-laboratory students had an average grade of 3.37. Although it is tempting to interpret these data, it is important to recognize the many confounding variables that must be considered, including differences in the faculty who taught the lecture component of the three sections of CHEM 115, as well as differences in the nature of the exams students had come to expect on the basis of their experiences in the different sections of CHEM 115. Furthermore, it would be important to know whether similar differences in performance in CHEM 116 occurred from year to year between students who used discovery laboratories in CHEM 115 and those who did not.

Conclusion

We have achieved at least the minimal level of success, the level at which discovery laboratories become an alternative to the traditional approach, from the perspective of both teaching assistants and students. We were able to implement discovery laboratories in a environment in which instruction is delivered by teaching assistants, even novice teaching assistants, in a manner consistent with the philosophy within which they were written. The TAs were not successful at all times, but they were all successful most of the time. Most of them had occasional problems, but these problems were neither frequent nor routine. Although they felt frustrated at times, most of the TAs would prefer teaching discovery laboratories in the future because they sensed

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that they played an important role in the development of their students' understanding. From the students' perspective, we achieved an environment in which they recognized that they could discover chemical concepts; they did not have to accept them solely on the basis of authority.

A significant level of success at which discovery laboratories become the preferred approach might have been achieved in terms of student attitude toward the laboratory. They appreciated working in an environment that did not suffer from the hidden assumptions of traditional laboratories, that is, the assumptions that students must work alone and that the experiment is "done" when they have finished collecting data. We have mixed results, at best, on the measure of whether or not discovery laboratories help students develop a *deeper* understanding of chemistry.

While the data collected in this study supports continuation of the discovery-laboratory program, there are still questions that need to be addressed by further research. What are the characteristics of the classroom environment that best suits the implementation of discovery laboratories? What personal, technical, or bureaucratic constraints [22] interfere with the implementation of discovery laboratories by other faculty or in other departments? What are the characteristics of the teaching assistants who are best able to implement discovery laboratories? How can we foster the development of these characteristics?

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