The Case for a Cooperative Studio Classroom: Teaching Petrology in a Different Way

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ABSTRACT

To improve our Petrology course, I have changed it from a lab-lecture format to one that emphasizes studio and cooperative learning. The goals of the changes are to: (1) improve student learning by covering (a smaller number of) topics in greater depth, (2) deemphasize knowledge-based learning and emphasize development of higher order thinking skills (comprehension, application, analysis, synthesis, evaluation), and (3) help our students develop good habits of the mind and fundamental skills useful for lifelong learning.

The reformatted course requires that students take more responsibility for their learning. I and the teaching assistant act as mentors, guiding students as they carry out the learning process. Lab and lecture sessions are seamlessly combined. Formal lectures are short and rare. Instead, students do many group projects, studying complex problems in depth. The content covered in the semester is less than in a more traditional class but the learning is greater.

After one semester, a multipronged assessment reveals that students like the redesigned course and believe they learn more than in a traditional course. They report no major problems. I, too, have found the redesigned course to be a success. It met all of the initial goals, was successful in many other ways, and will lead to improvements in other classes and in our curricula.

INTRODUCTION

At the University of North Dakota, Petrology (Geology 320) is a junior level course required of all majors that covers general igneous and metamorphic petrology. I inherited Geology 320 from another, now retired, instructor several years ago and have not been particularly happy with the way I teach the class. I have experimented with different curricula and teaching strategies. As with many of my classes, I have found myself moving away from lectures and more toward cooperative learning and other group activities. This approach means we cover fewer topics but we cover them in greater depth.

There are several reasons why I have moved away from traditional teaching strategies; the most important being that there are better ways to promote student learning. Many teachers have found that active learning, including cooperative learning and group activities, helps students learn, and especially to develop higher order thinking skills including comprehension, application, analysis, synthesis, and evaluation. While actively engaged, students develop good habits of the mind and the skills needed to be successful lifelong learners (Welch et al., 1981; Gabelnick et al., 1990; Bosworth and Hamilton, 1994; Macdonald and Bykerk-Kauffman, 1996; Srogi and Baloche, 1997). Additionally, many studies support the notion that "less is more," meaning that exposing students to less information can lead to better learning (e.g., Tobias, 1990; Dempster, 1993; Nelson, 2001; Fratt, 2002; D'Avanzo, 2003, and references therein).

At the University of North Dakota, the the Bush Teaching Scholars Program brings together faculty dedicated to investigating significant issues related to teaching and learning in their fields. The program, funded by the Archibald Bush Foundation (Minneapolis) is designed to create a faculty learning community focused on the scholarship of teaching that extends beyond the borders of our university. In the fall, 2003, as part of my participation in the Bush Program, I made significant changes in my Petrology class. I eliminated nearly all remaining lecturing and focused the class on cooperative and active learning by the students. To facilitate this, I integrated the "laboratory" and "lecture" parts of the class, and adjusted class meeting times to be much longer than the usual 50 minutes or an hour. In essence, I converted my classroom from the standard lab-lecture format to what some call a "studio classroom" with a focus on cooperative learning. Although the total contact hours are about the same, the class now only meets for the first 10 weeks of the 16-week semester. The reformatted class was so successful that I am now planning to change my mineralogy class in the same way.

VALUE OF THE STUDIO CLASSROOM

Some instructors at other schools have successfully used the studio format. Laws (1991), Young (1996), Walter and Hendler (1996), Wilson (1994, 1997), Rumsey (2000), Beichner and Saul (2003), Belcher (2004), and Handelsman et al. (2004) provide some basic background and discussions of the studio approach. The printed literature on studio teaching is surprisingly skimpy, however, perhaps reflecting its relatively short history. Still, many short pieces can be found on the web, and are easily tracked down using standard search engines. Most of the web articles and reports come from just a few schools, including especially the Rensselaer Polytechnic Institute, North Carolina State University and the California Polytechnic State University, where some departments and instructors emphasize studio learning (especially in physics and engineering). At these institutions, studio classrooms often involve computer clusters and work stations, so many reports focus on technology (e.g., Ross, 2002). The benefits and principles of studio teaching, however, do not require such technology.

The idea of studio learning originated, perhaps, in architecture and art programs and more recently has grown in engineering and technical schools. Many instructors have successfully used cooperative learning in their classrooms; studio teaching is a logical extension of that approach. Studio classrooms have many different manifestations but all share common elements. They involve longer, fewer, class sessions with focused, intense, student activity. Any disconnect between laboratory and lecture time is absent because lab and lecture are combined. In fact, lectures are de-emphasized

Characteristics	Cooperative Studio Course	Traditional Lecture - Laboratory Course
Meeting times	two times per week for 3 hours or more	two or three 50 or 90 minute lectures and one lab per week
Lectures	rare and generally no longer than 15 to 20 minutes	lectures account for at least half the class time and last 50 to 90 minutes
Lab exercises	not separated from lectures; generally group activities	completely separate from lecture; generally individual activities
Group activities	the focus of the class	rare; sometimes in lab sessions
Role of instructor	learning guide; class coordinator; a resource for students when needed	authority; lecturer
Instructor's time	5 to 6 contact hours per week; both lab and lecture activities	2.5 to 3 contact hours per week; generally only in lecture sections
Role of teaching assistant	aid instructor; acts as student resource	oversees lab sessions
Role of students	active learner; group participant; control their own learning environment; learn by doing	passive learners; learn what is required; mostly work as individuals
Curriculum	cover a smaller number of topics in great depth	cover many topics but not all in great depth
Examinations	(perhaps?) not useful or needed	several during a semester and a final exam
Grading	based on individuals and what they did	based on class averages

Table 1. Comparison a cooperative studio classroom with a more traditional one.

or eliminated altogether. Students work on in-depth projects instead, generally in groups, sometimes moving from one workstation to another. Tables or benches are arranged so students face each other instead of the front of the classroom. The interactive classroom promotes holistic skills, including thinking, inquiry, creativity and reflection by students, frequently involving peer review and critiquing. Table 1 compares some characteristics of a course taught as a cooperative studio class with those of a more traditionally taught science class.

A properly managed studio classroom can provide a quintessential active and cooperative learning environment. The value of such an environment has been well described by many. See for example Welch et al. (1981), Macdonald and Bykerk-Kauffman (1996), Srogi and Baloche (1997), and articles by several authors in Inquiring into Inquiry Learning and Teaching in Science (Minstrell and van Zee, 2000). Additionally, studio teaching is consistent with goals summarized in National Research Council reports including National Science Education Standards (NRC, 1996) and From Analysis to Action: Undergraduate Education in Science, Mathematics, Engineering, and Technology (NRC, 1996). It also matches recommendations in the AAAS publication Science for All Americans by Rutherford and Ahlgren (1991), and in the NSF report Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering , and Technology (NSF, 1996). In these reports, and others, emphasis is placed on getting students actively involved in doing science and thinking like scientists. In its executive summary, the NSF report recommends that ". . . all students learn [science] by direct experience with the methods and processes of inquiry." While doing, thinking, and inquiring, students learn science and also develop key skills including collaboration, teamwork, communication, and responsibility.

An important characteristic of studio classrooms is that students have more control and responsibility for outcomes than in traditional classrooms. Instructors and teaching assistants (TAs) are mentors, acting as learning guides, providing the learning environment and materials needed for students to create their own learning. Instructors help students start on projects and are on hand as resources for students to use. Besides the instructor, learning resources include traditional texts and other reading materials, and also student peers in a class. Consequently, a key to success is that students must attend class and everyone must participate; this requires some adjustment by students who have not experienced such a classroom environment before. Most students, however, do catch on and in the end find it easier to attend fewer classes even if they are of longer duration.

Anecdotal reports and qualitative evaluations of studio teaching and learning by both instructors and students are overwhelmingly positive. Few, however, have conducted quantitative assessments comparing the effectiveness of studio teaching to more traditional approaches. Some studies show equal or better content mastery by students in studio classrooms compared with traditional classrooms (e.g., Wilson, 1997; Gaubatz, 2003; Beichner and Saul, 2003) but content mastery is only one of many potential teaching goals. Other studies (see references cited by Gaubatz, 2003) that have compared classes taught in different scheduling formats suggest that, for most students, time-intensive courses "produce comparable or enhanced academic achievement" (Gaubatz, 2003; see also Nahrgang, 1982; Bateson, 1990; Caskey, 1994; Scott, 1996, 2003; Henebry, 1997; Van Scyoc and Gleason, 1993). In studies of non-traditional teaching practices, most researchers find that innovative approaches to teaching work for most students most of the time. I suspect that some success is due to instructor enthusiasm, but some is also because traditional classrooms are not generally optimal for promoting student learning.

In studio classrooms, the processes followed in the classroom are just as important (perhaps more important) than the topics covered. Instructors base grading in large part on what the student does and how they develop intellectually. So, instructors must monitor student progress continually by observing student behavior, talking formally and informally with students,

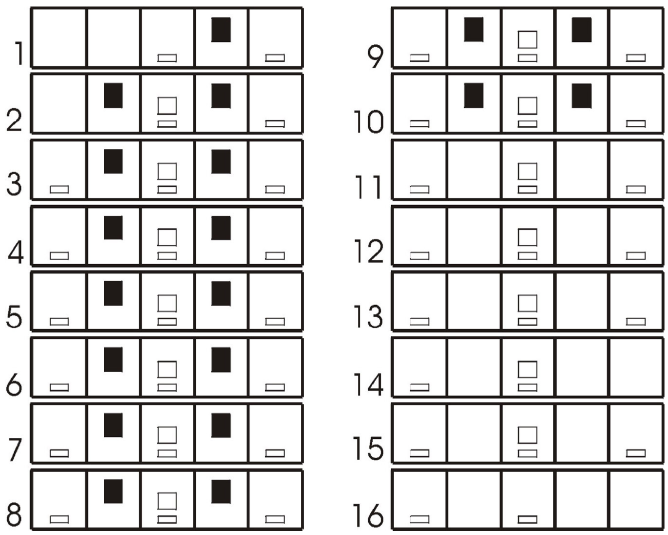

Figure 1. Class meeting times during the 16 week semester. Open boxes are the way it was done before 2003, dark boxes show the new schedule. Some blank days correspond to holidays.

using various short assessment activities, and other means. Traditional measures of learning that focus on content mastery, such as objective exams, receive less emphasis. Consequently, a problem with changing from a traditional teaching format to a studio format is that lecture notes, projects, exams - all course materials - need to be redesigned. Although the instructor does not lecture in traditional ways, preparation takes lots of time and planning must be well done. Presenting the same material in fewer, but longer, time slots does not work. Evaluating students using standard objective exams may be inappropriate. In fact, in my studio classroom, I am not sure that exams are a good use of any of our time. (See Tewksbury, 1996, for a discussion of the value and problems associated with an "exam-less" classroom.)

CLASSROOM AND CLASS SCHEDULING

Studio teaching is not really possible in traditional lecture halls because effective group activities require that students sit together and look at each other. Some schools have purchased new furniture and completely redesigned classrooms, especially if their studio teaching involves heavy use of computers. Fortunately, we did not have to do any major redesign because we are not focusing on computers and because our Petrology classroom has large laboratory tables allowing students to sit opposite each other.

At UND, like at most colleges and universities, class lecture sessions meet for three standard 50 minute periods, or two 80 minute periods per week. Lab sessions are generally 2 hours or longer in the afternoons. To conform to this scheduling system, we have now scheduled our petrology lectures and labs back-to-back on Tuesday and Thursday afternoons. The class meets for only the first 10 weeks of the 16-week semester. The "shortened" semester, implemented because of university expectations regarding contact hours and credit, gives students a more focused learning experience. Despite fewer weeks, the class included

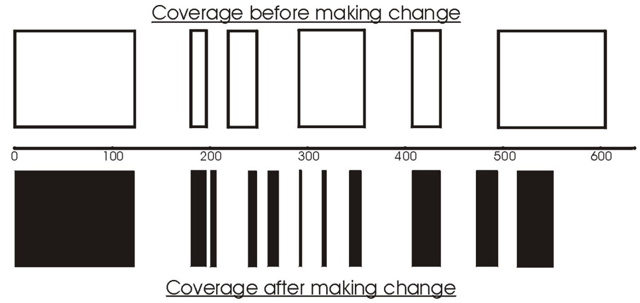

Figure 2. Comparing the amount of material including in Petrology now and in the past. The horizontal scale refers to page numbers in Winter's (2001) book.

about 63 contact hours this past semester, compared with 65 contact hours in prior semesters.

Figure 1 shows the class meeting time now compared with the way it was done before 2003. The old schedule involved three morning lectures and one afternoon lab. Now, although the official university time schedule lists lab and lecture separately, they are seamless and meet from 2 to 5 PM two days a week. Often students get so engaged in their projects that they stay until 5:30 or 6:00.

CURRICULUM

I use Winter's An Introduction to Igneous and Metamorphic Petrology (2001) as the main textbook for Petrology. Winter's book and other available petrology texts contain more information than any semester class can cover, no matter the format. Every instructor decides what to include or not include in their course; Table 2 summarizes the major topics in our Petrology class.

As many teachers have discovered, changing from lecture-based teaching to a classroom that incorporates more active learning required a decrease in the amount of material covered. Although I was prepared for this adjustment, its size was greater than expected. To give a sense of the change, Figure 2 compares the material covered before and after we rescheduled Petrology. The arbitrary scale used for visual comparison is based on the page numbers in Winter's book. The pages indicated are those the students read in support of our classroom activities.

TYPICAL CLASS

Three hours is a long time for a class to meet. While keeping students focused is important, avoiding boredom and tedium requires some variety. Class sessions varied, but our typical class might be:

15 minute mini-lecture
45 minute group project
15 minute discussion or mini-lecture
90 minute group project
30 minutes reporting / discussing

The group projects, key to the success of this class, emphasized cooperative and collaborative activities (Macdonald and Bykerk-Kauffman, 1996; Srogi and Baloche, 1997; Tewksbury, 1996). Projects included discussions, debates, presentations, paper and pencil

Igneous Petrology	Metamorphic Petrology
introduction to petrology	what are metamorphic rocks?
chemistry of igneous rocks	P, T, X and minerals
phase rule and phase diagrams	phase equilibria and thermodynamics
petrogenesis	thermometry and barometry
basalts and ultramafic rocks	contact metamorphism
rhyolites, andesites, and pyroclastics	regional metamorphism
ultramafic rocks of all sorts	blueschists and eclogites
granites, calc-alkaline and alkaline rocks	igneous and metamorphic rocks in tectonic settings

Table 2. Topics covered in petrology, Fall 2003.

Activity	Creator
"Illustrating Fractional Crystallization with an M&M Magma Chamber"	Karl Wirth, Macalester College
"Using Kitchen Chemistry and the Concept of Saturation to Help Students Understand Igneous Phase Diagrams"	John B. Brady, Smith College
"Laboratory on Pelitic Rocks"	Jane Selverstone, University of New Mexico
"Calculating Pressures and Temperatures of Petrologic Events"	Donna L. Whitney, University of Minnesota

Table 3. Activities and their creators.

exercises, computer projects and, in most classes, work with hand specimens or thin sections.

The projects were multifaceted and often took more than one class session. For example, when we considered the order in which minerals crystallize from a magma, students read the relevant sections in the textbook prior to coming to class. During class we started with a brief quiz, involving individual and group responses, to confirm they had done the reading. The quiz was followed by discussion of congruent and incongruent melting and Bowen's Reaction Series. We next looked at phase diagrams, discussed how to interpret them, and did some calculations and comparisons involving melting temperatures and products for different rocks and different minerals. We then examined a dozen rocks and thin sections, identified the minerals in them and gave the rocks names, and used textures to infer the order in which minerals crystallized. To end the day, students began modeling crystallization/differentiation using Karl Wirth's M&M Magma Chamber Exercise (Table 3). In the next class session, they finished crystallizing and analyzing the M&M's, discussed layered igneous complexes and how they form, and talked about cumulates. For homework, the students had read articles on the Stillwater and Bushveld complexes, and so some gave presentations to the class. Then we looked at maps, hand specimens and thin sections from those places, and the students answered a series of "guided inquiry" questions as a final activity. All of these activities were group activities involving 3 or 4 students in each group.

We derived some of the most successful class activities, including Wirth's, from presentations at the NSF sponsored "Teaching Petrology in the 21st Century" Workshop (Montana State University, Bozeman, MT, June 9-15, 2003), part of the larger program: "On the Cutting Edge: Workshops for Geoscience Faculty." Some descriptions of activities introduced at the workshop can be found at http://serc.carleton.edu/NAGTWorkshops/petrology03/redirect.html. Table 3 lists four of the class projects rated most highly by students that can be found on the workshop web site.

CLASS ASSESSMENT

To provide insight and to help maintain objectivity, a colleague in the Bush Teaching Scholars Program served as a teaching consultant. His participation was key because he worked closely with the students (meeting weekly with them) to provide formative assessments of the class. Additionally, because he was intimately familiar with the project, he provided valuable conversation and suggestions.

Some instructors have collected hard data demonstrating that studio teaching promotes better learning (including problem solving skills and better understanding of key concepts), improved student attitudes, and better grades (e.g., Beichner and Saul, 2003). While documenting student attitudes and grades was no problem, I found it extremely difficult to make objective comparisons of learning outcomes between Petrology taught as a studio class, and the way I taught it before. If only the format of the class had changed, comparison of exam and project grades, and use of traditional assessments would be adequate to evaluate improvements in student learning. As the consultant and I started the assessment process, however, we soon realized that the goals of the class had changed significantly, and that previously used exams and grading techniques were not appropriate for the redesigned class. Additionally, the enthusiasm and time invested by the instructor, TA, and consultant were much greater than in previous semesters. Consequently, although we can use many indicators to compare learning in the class before and after reformatting, we have no quantitative data. Others have encountered this problem, as alluded to above, while trying to assess the effectiveness of alternative teaching strategies.

Instrument/Method	Purpose
two kinds of pre- and post-course surveys	to evaluate changes in student attitudes toward learning, to evaluate the kind of learning that occurred
weekly formative assessments (once a week, students discussed the class with the teaching consultant in the instructor's absence)	to give students a sense of ownership of the class, to determine what was working, to adjust and fine-tune as needed
teaching journal kept by instructor (entries 1-4 times a week while preparing for the class and also while it took place)	to encourage introspection, to permit me to go back and assess what issues I dealt with and when
post-class student interviews (several small groups)	to expand on some ideas and concerns
student performance on projects, quizzes, and exams	to measure learning and progress toward class goals

Table 4. Assessment instruments and methods.

What Sort of Learning is Taking Place?

Bloom et al. (1956) classify learning into six categories, summarized below. Students were asked to estimate how much time they thought the class will / did devote to each of the six general categories, using this scale:

1=almost none 2= minor focus 3=some of the time 4=major focus 5=almost all of class

Before the students completed this survey, we took about 15 minutes to discuss learning and Bloom's Taxonomy. The survey was conducted during the first class meeting and then again at the end of the semester. Before and after responses are separated by an arrow. The survey instrument is based on material available at Counseling Services, University of Victoria (2003).

Competence	Skills Demonstrated
Knowledge $4.2 \rightarrow 2.9$	observation and recall of information knowledge of dates, events, places knowledge of major ideas mastery of subject matter
Comprehension $2.8 \rightarrow 3.9$	understanding information grasp meaning translate knowledge into new context interpret facts, compare, contrast order, group, infer causes predict consequences
Application $2.2 \rightarrow 4.2$	use information use methods, concepts, theories in new situations solve problems using required skills or knowledge
Analysis $1.9 \rightarrow 2.2$	seeing patterns organization of parts recognition of hidden meanings identification of components
Synthesis $1.9 \rightarrow 2.4$	use old ideas to create new ones generalize from given facts relate knowledge from several areas predict, draw conclusions
Evaluation $1.6 \rightarrow 3.4$	compare and discriminate between ideas assess value of theories, presentations make choices based on reasoned argument verify value of evidence recognize subjectivity

Table 5. What Sort of Learning is Taking Place?

Table 4 summarizes five different ways we assessed the class. Our multipronged approach was designed to provide formative assessments to allow adjustments and fine tuning during the semester, and also to allow evaluation of the effectiveness of the studio approach to teaching.

STUDENT PERSPECTIVE

One goal of the redesigned class was to promote higher levels of learning (not just content memorization). Although I designed the curriculum with this in mind, I realized that I needed a way to assess this goal. So, I used an instrument based on what is now commonly called Bloom's Taxonomy (Bloom et al., 1956) to see what the students thought they had learned (Table 5). Bloom and his colleagues classified the cognitive domain (now frequently equated with learning) into six categories: knowledge, comprehension, application, analysis, synthesis and evaluation. According to Bloom et al. (1956) this order goes from low order cognition (recall of memorized information) to higher order cognition (greater intellectual development). During the first class meeting, I asked students what sorts of learning they thought they would experience during the semester. They responded in the same order in which Bloom et al. (1956) presented their categories, indicating they believed that knowledge (learning facts) would be the most significant aspect of the course. At the end of the semester, however, they said that most of their learning was of higher order. Much fell in the application category. Comprehension came second, evaluation third and knowledge was only in fourth place. The students' conclusions agreed with those of the instructor and the consultant. Throughout the semester, the students had amazed us with their ability to synthesize and apply data in different situations.

In the weekly meetings with the teaching consultant and in interviews after completion of the course, students said that the studio classroom was successful in promoting learning and that they preferred it to a traditional classroom. For example, during the interviews the following comments were recorded:

"Working with other students is much better than working alone. Not only does it help you understand things, but having responsibility to your classmates means you have to show up and contribute."

"There were so many ways to learn things in this class - if we didn't get it one way, we figured it out another."

Attitudes Assessment

This survey, based on a survey instrument developed by Williamson and Rowe (2002), was administered during the first and last class sessions. Numbers after each question show the average initial and final response based on the 7 point Likert Scale.

Strongly Agree			Neutral	Strongly Disagree		
1	2	3	4	5	6	7

16 or 17 students participated in this and the other assessments. Underlined bold statements and scores indicate significant changes in student responses.

Question #	Statement	Likert Scale	
		Before	**After**
1	I like to read textbooks.	4.5	4.5
2	**I learn a great deal by reading textbooks**.	**3.5**	**4.3**
3	I feel more comfortable about what I am learning when I have a textbook to read.	3.1	3.3
4	Often, I learn a lot from answering questions at the end of chapters.	4.1	4.3
5	**I prefer to read a textbook before a topic is discussed in class**.	**3.9**	**4.9**
6	I enjoy working in a group to solve problems and do assignments.	**2.3**	**1.8**
7	**I understand material better and learn more when I work with someone else to solve problems and do assignments**.	**2.4**	**1.7**
8	A serious problem with group projects is that some people do most of the work while others get a "free ride".	3.4	3.1
9	I feel comfortable asking questions during class.	2.8	2.9
10	I learn more when I hear another student's viewpoint.	2.7	2.4
11	**I am comfortable discussing things with other students in my class**.	**2.4**	**1.8**
12	My participation contributes to what I learn in a class.	2.9	2.6
13	The methods others use to work problems may be different than mine.	2.2	2.3
14	**I learn more by listening to a lecture than I do by doing projects or working problems**.	**4.1**	**5.4**
15	In general laboratory activities involving rocks and microscopes, etc. Are better learning activities than paper or pencil in-class activities.	3.1	3.0
16	**Term papers and other individuals projects often contribute significantly to my learning.**	**3.6**	**4.1**
17	Although having students give presentations in class may help develop speaking skills, it is NOT an efficient use of class time.	3.1	3.1
18	Giving class presentations is a good way for the speaker to learn things.	2.2	2.3
19	Having students give class presentations is a good way for the listeners to learn things.	5.5	5.3
20	**Having separate lab and lecture meeting times helps improve learning**.	**2.9**	**3.6**
21	I learn more in classes if they meet more than two times a week compared to classes that meet less often but for longer times.	3.8	4.0
22	**It is important that I am present every time a class meets**.	**3.4**	**2.7**
23	I learn best if a course lasts a whole semester instead of being focused in a shorter time period.	3.6	3.4
24	**The teacher's job is to present the material. It is my job to learn it**.	**4.6**	**5.1**
25	I am very concerned about the grade I get in a class, not so much about what I actually learn.	3.8	4.2

Table 6. Attitudes assessment.

The students' overall satisfaction was confirmed by their responses on an Attitudes Assessment (Table 6). For this survey, they ranked a number of factors using a Likert (agree/disagree) scale. Perhaps more significant than their specific responses were the changes between the beginning and end of the semester. This class clearly changed their attitudes about what best promotes learning. At the end of the semester, they gave especially high marks to group problem solving. They gave relatively low marks to textbooks, lectures, individual projects. They acknowledged the need to be present in class and said they learn best when lab and lecture are combined. In post-class interviews all except one student (out of 17) said that the class was challenging, that they did not get enough credit for it, but that they learned a lot while having fun. One student said:

"I worked my tail off in this class but it was fun and I learned more than in any other of my science classes."

From the student perspective, every major aspect of the class was a success.

INSTRUCTOR PERSPECTIVE

My assessment and that of the teaching consultant echoed the students' in most ways. We found the class to be very successful for all the same reasons, and we also found other benefits. In every class session, students were involved in active learning involving thinking, inquiry, creativity and reflection. They "did" and "thought about" science in the way that scientists do, as they developed skill at collaboration and teamwork. Scores on exams and other evaluations suggest that, besides the holistic skills, they learned as much, or more about petrology than students had in previous semesters. The cooperative environment and combined lecture/discussion/lab format allowed us to get students involved in multifaceted investigations that would have been impossible previously.

One unanticipated characteristic of our studio classroom was that the TA and I found it quite easy, and absolutely necessary, to keep track of student progress and success. Due to the nature of the pedagogy and the projects, student-instructor contacts occurred more often and more meaningfully. We could give different students and different groups as much or as little of our time as they needed. If a project appeared very successful, expanding it to promote even greater learning was easy - for just a few students or for the entire class. If a project was not working, we could adjust, perhaps by providing more supporting information. We soon learned that different groups and different individuals worked at different paces. If they mastered one thing, they moved on to something different. If they were struggling, we could give them extra attention. Additionally, because different groups were doing different things, we rarely had problems with students having to wait to use limited resources such as rock samples, thin sections, microscopes, cameras or computers.

Although our overall assessment is very positive, we had a few difficulties and misgivings, mostly unnoticed by the students. For one thing, because this class was so student-focused, it required giving up a sometimes uncomfortable amount of control. At times I hovered with nothing to do because the students didn't need me in the classroom. On review, I find that I mentioned this problem half a dozen times in my teaching journal, questioning whether I was giving students everything I should. By the end of the semester I felt comfortable with my redundancy, but during the semester I sometimes worried quite a bit.

The biggest problem encountered was time. This problem manifested itself in several ways. First, due to lack of time, I found that I could not cover some material that I originally thought essential to the class. By the end of the semester, I was quite happy with the curriculum, but I had to make adjustments as we went along. Several colleagues have questioned whether I covered all topics that are essential to a Petrology class. I cannot answer this question unambiguously because different people consider different things essential. (At the "Teaching Petrology in the 21st Century" Workshop, a survey of about 100 petrologists, all of whom are committed teachers, revealed no consensus on what was an ideal curriculum.) Additionally, helping students to develop basic thinking skills, and to develop good habits of the mind, may be more important than covering more topics in a course (Tobias, 1990; Dempster, 1993; Nelson, 2001; Fratt, 2002; D'Avanzo, 2003). While I believe I did cover all requisite topics, I still see a need for further assessment to address this question. In particular, I plan to use knowledge surveys (Nuhfer, 1996; Nuhfer and Knipp, 2003) in this class beginning the next time I teach it. Knowledge surveys will allow me to clarify goals and to evaluate whether we are reaching them.

A second time problem involved use of my time. This class required me to commit nearly twice as many contact hours as I did in past years. It was not possible or appropriate to turn over all lab activities to the TA. Additionally, class preparation required many hours of my work each week, including careful and time-consuming preparation of handouts, samples, microscopes and other things. As much as possible, I intended to introduce and distribute assignments and then stand aside while students performed. This does not mean I "dumbed down" the projects. In fact, the longer class periods and group projects made it possible to investigate challenging topics in great depth, thus promoting higher levels of learning. However, careful planning was required for these projects to be successful. I hope, and anticipate, that the preparation time will be less next time I teach the class.

Few lectures meant that organization and flow of course had to come in other ways. The curriculum needed to mesh well, and projects had to fit together and move the class toward specific goals. If students were to work together in cooperative groups without instructor input for long periods of time, they needed to stay on task. So, assignments and expectations had to be especially clear to students. Despite our best efforts at preparation, individuals or groups occasionally lost focus or became distracted by tangents. We took care to monitor what students were doing because we thought it important to help them stay on task. Yet, in my teaching journal I noted several instances where we may have intervened prematurely. In retrospect, the students might have gained more if we had given them longer to determine their own directions.

To maximize higher level learning, we found it absolutely necessary to take time to review and discuss outcomes at the end of each project, more than we had (perhaps unwisely) in our traditional class. Because students worked in groups, closing the learning loop required bringing the groups together to compare results. Besides discussing results, we often analyzed and critiqued the projects themselves during these discussion sessions. The plenary sessions produced some of the best teachable moments of the whole semester.

A more pedestrian problem was giving students credit for what they did so we could assign individual grades. Student responses on the assessment survey revealed no concerns about unequal participation in group activities, although I had some concerns. Clearly, some students contributed more to group activities than others and perhaps deserved more credit. An additional complication arose because one student preferred to work alone on some projects. Consequently he ended up doing much more work than some of his colleagues. Besides group projects, the class included several individual exams, quizzes and class presentations. Ultimately these individual activities were weighted quite heavily when calculating student grades. We probably undervalued group accomplishments. Because I am not sure I will have any exams the next time I teach the class, I may have to find another way to evaluate individual students.

ACKNOWLEDGMENTS

This project would not have been possible without support from the University of North Dakota's Bush Teaching Scholars Program (funded by the Archibald Bush Foundation, Minneapolis, Minnesota,) and UND's Office of Instructional Development. Valuable ideas and input came from discussions with other UND Bush Scholars, especially from Frank White who acted as teaching consultant. Reviews by Steve Semken and two others helped improve the manuscript.

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