BIOCHEMISTRY AND MOLECULAR BIOLOGY EDUCATION
Vol. 35, No. 3, pp. 172–180, 2007

Articles

Lecture-free Biochemistry

A PROCESS ORIENTED GUIDED INQUIRY APPROACH

Received for publication, September 18, 2006, and in revised form, December 22, 2006

Vicky Minderhout‡ and Jennifer Loertscher

From the Department of Chemistry, Seattle University, Seattle, Washington 98122

Biochemistry courses at Seattle University have been taught exclusively using process oriented guided inquiry learning (POGIL) without any traditional lecture component since 1997. In these courses, students participate in a structured learning environment, which includes a preparatory assignment, an in-class activity, and a follow-up skill exercise. Instructor-designed learning activities provide the content of the course while the cooperative learning structure provides the content-free procedures that promote development of critical process skills needed for learning. This format enables students to initially explore a topic independently, work together in groups to construct and refine knowledge, and eventually develop deep understanding of the essential concepts. These stages of exploration and concept development form the foundation for application to high level biochemical problems. At the end of this course, most students report feeling confident in their knowledge of biochemistry and report substantial gains in independence, critical thinking, and respect for others.

Keywords: Active learning, learner-centered teaching, POGIL.

Process oriented guided inquiry learning (POGIL), an NSF-funded project, is a widely used active learning approach that was pioneered in chemistry. POGIL involves creating a learning environment in which students actively engage in mastering a discipline and in developing essential skills by working in self-managed teams on guided inquiry activities (www.pogil.org) [1–3]. Thus POGIL promotes learning of course content, while simultaneously developing in students important process skills including information processing, critical thinking, problem solving, teamwork, and communication. Published POGIL materials are available for general, organic, physical chemistry, and GOB (general, organic, and biochemistry) courses [4–9]. The effectiveness of POGIL in general chemistry has been previously described [1, 10].

Here we describe our application of POGIL principles to the biochemistry classroom through creation and implementation of 30 biochemistry activities. The approach described here is by no means the first attempt to teach biochemistry in an active learning format. Problem based learning [11, 12] and case-based instruction [13–15] both rely on active learning to promote skill development in biochemistry; however, the materials we developed and utilize are distinct from these approaches in that they use guided inquiry for conceptual development and enhance student problem solving using single class period activities. Availability of single class period activities is essential in promoting gradual adoption of active learning by a wide variety of instructors. Our implementation of POGIL biochemistry has been highly successful as evidenced by our student's performance and perception of achievement in acquisition of higher order cognitive, social, and affective skills.

BACKGROUND

Modern research on how people learn confirms that knowledge must be constructed within the mind of the learner [16–18]. This construction of knowledge is best facilitated in the presence of faculty who serve to monitor and promote learning while helping students confront misconceptions and improve thinking processes. The social context of using cooperative teams for learning helps make thought processes apparent to teachers and to students. In this way the faculty member can promote learning while the students recognize the criteria for competence observed in others to improve their own performance. As a result, students learn best when they are actively engaged in a meaningful social context while constructing understanding and solving problems [19].

Active learning can include many forms within the classroom and laboratory. The framework for active learning that informs our work begins with an understanding of Bloom's taxonomy of educational objectives [20]. Bloom articulated six levels of thinking in the cognitive domain: knowledge, comprehension, application, analysis, synthesis, and evaluation. Students cannot apply newly acquired knowledge if that knowledge is incomplete, poorly understood, or unconnected to prior

‡ To whom correspondence should be addressed.
E-mail: vicky@seattleu.edu.

DOI 10.1002/bambed.39

TABLE I
Course goals for POGIL biochemistry

Cognitive	Affective	Social	Lifelong learning
Acquire and master vocabulary of biochemistry	Obtain a belief in one's ability to learn and apply the material	Work cooperatively and demonstrate commitment to a group	Become self-directed: Initiate the learning process
Organize information	Advance intellectual tolerance and integrity	Listen to and learn from peers	Become self-reflective: Review goals, purposes, outcomes, and new learning
Understand complex relationships in biochemistry	Set personal goals for improvement and ask for help	Value others	Become a self-assessor: Assess one's own progress for strengths, areas for improvement and insights into the learning process to continuously improve
Improve visualization and modeling skills			
Improve problem solving skills by asking questions and examining assumptions			
Analyze and interpret data			
Apply knowledge to new situations			
Develop the ability to select appropriate actions and/or tools			

Goals stated are applied to the content of each course, specifically, protein and lipid structure and functions (Biochemistry 1); nucleic acid biochemistry (Biochemistry 2); and metabolism (Biochemistry 3).

knowledge. Well-conceived active learning materials help students connect with and build upon prior knowledge, extend that knowledge base with new concepts and ultimately provide new contexts for a rich learning environment. POGIL incorporates Bloom's levels by employing a learning cycle paradigm, which includes exploration, concept invention, and application. [1, 21–23]. As discussed by Miller, Groccia, and Wilkes, structure, such as that imposed by implementation of the learning cycle, is essential in an active learning classroom [24].

Learning in biochemistry presents several challenges, one of which is the magnitude of knowledge in the field. The volume of information is expanding at such a rate that learning all of the content is an unreasonable proposition. As a result, development of fundamental skills that can be applied to address unfamiliar problems is critical. Another challenge is that biochemistry builds on fundamentals taught in all sub-fields of chemistry and biology. Students are confronted with few new concepts and application is the norm. Application by its nature requires high level cognitive skills and often includes problem solving. Such skills are not learned through lecture, but rather through active application of fundamental principles to explore relationships inherent in biochemistry and to solve unfamiliar problems [25, 26]. However, practicing such skills without feedback produces little learning; in fact doing things incorrectly is counterproductive [27], whereas formative assessment during class produces significant improvement in performance [28]. An active learning classroom, as used with POGIL, allows instructors to provide timely and informative feedback to students, thereby improving the effectiveness of higher order cognitive processes [29, 30]. Faculty with this mindset view themselves as coaches in the development of essential cognitive, social, and affective skills in their students.

COURSE CONTEXT AND GOALS

Seattle University is a comprehensive Jesuit university with an undergraduate population of about 4,100. Biochemistry at Seattle University is offered to juniors and seniors and has been taught using a lecture-free format since 1997. We currently teach a year-long (three quarters) sequence of POGIL biochemistry using a comprehensive set of approximately 30 activities that cover the structure and function of proteins in aqueous and lipid environments, techniques of biochemistry, intermediary metabolism, and selected activities on structure and function of carbohydrates and lipids. The topics of replication, fidelity of replication, DNA repair, and translation are taught from the primary literature using an active learning approach. Many of the activities provide focused problems that help students practice solving difficult problems. Biochemistry 1 (first quarter) focuses on protein and lipid structure and function, Biochemistry 2 (second quarter) on nucleic acid biochemistry, and Biochemistry 3 (third quarter) on metabolism. One section of each course is offered in a typical year, with the largest enrollments in Biochemistry 1 and 3. Typical enrollments range from 15–30 students, with the exception of first quarter, which has approximately 40 students. For the past three years, the first quarter course has been team taught with two instructors in the classroom at all times. Course enrollees are nearly equally divided between biology, chemistry, and biochemistry majors. Approximately thirty percent of students are on a pre-medical or pre-dental track.

The course goals, shown in Table I, are broader than is typical for a biochemistry course. Cognitive goals for the

TABLE II
Descriptions of course components for POGIL biochemistry

	Pre-activity assignment	In-class activity	Post-activity skill exercise
What would this be similar to in a traditional class?	Preparation for class	Lectures notes	Homework, problem sets
When is it due?	At the beginning of class	Complete as a group during class	At the beginning of the following class
Who turns it in?	Each individual	One copy per group	Each individual
How is it graded?	Full credit will be given for adequate completion	Not graded, but written feedback will be given	Graded based on correctness of answers
What do students get out of completing it?	First exposure to a topic so that students are prepared to deal with the topic more deeply in class; points	Practice at formulating high quality responses; hearing what others think to refine own thinking	Practice applying what was learned in groups; points
What do students get out of looking at it again after it is returned?	Instructors may write comments to direct students if they are missing a major point or could prepare more efficiently	Instructors write feedback to let students know if they understand concepts and if answers were communicated clearly	Keys are posted so that students can check answers

course include not only mastery of relevant biochemistry subject matter, but also acquisition or enhancement of basic scientific skills, including data analysis, formulation of appropriate questions, and application of knowledge to complex situations. Although many biochemistry instructors have these higher-order thinking skills in mind as learning goals, the structured, active learning format of our approach enables us to directly observe student performance in these areas and to coach students on strategies for improvement in real time. In addition to fostering higher order cognitive skills, we also expect our students to meet affective, social and lifelong learning goals (Table I). These fundamental process skills, including teamwork, an ability to set goals, and a belief in one's ability to learn, are essential for students' future success in life and the workplace, regardless of whether they intend to pursue academic, research, or health professional careers. All course goals are clearly communicated to students in the course syllabus.

IMPLEMENTATION

Activities Are Based on the Learning Cycle and Are Sequenced Using Bloom's Taxonomy

Our classroom activities were developed to follow a broadly defined learning cycle model including exploration, concept invention, and application [3]. The learning cycle incorporates the first three levels of Bloom's taxonomy: knowledge, comprehension, and application. In a typical POGIL activity, students are presented a model and then guided through the learning cycle towards understanding the chemical principles underlying the model. This is accomplished through a sequence of directed, convergent, and divergent questions [1, 2]. In POGIL activities designed for general and organic chemistry, students are presented with a model and are asked all three types of questions within the context of a single in-class activity. In contrast to general and organic chemistry courses, which teach foundational chemical concepts, biochemistry focuses on application of chemical principles to complex biological systems. Furthermore, all students in our biochemistry course have successfully completed general and organic chemistry. As a result, we ask students to complete nearly all exploration of a topic before arriving to class by preparing a reading outline of relevant chapter sections from the textbook. By requiring students to prepare, class time can be devoted to development of challenging concepts and application of newly acquired knowledge to solve problems. Our activities include three components for each class day: a pre-activity assignment, a classroom activity, and a post-activity skill exercise (Table II). Taken together, this structure follows the learning cycle and guides students to develop and apply fundamental biochemical concepts.

To understand the function of each component of our guided inquiry activities, consider the enzyme catalysis activity, which has four learning outcomes:

1. Apply your understanding of intermolecular forces to rate enhancement.
2. Explain general acid–base catalyzed reactions and apply to enzyme-catalyzed reactions.
3. Generalize your understanding of rate enhancement of an acid/base catalyzed reaction to other types of enzyme-mediated catalysis.
4. Integrate your understanding of rate enhancement and rate determining step in ΔG *versus* reaction coordinate diagrams.

The pre-activity assignment includes outlining the reading; students are required to generate notes and two quality questions. A quality question is one in which the student attempts to connect the new material with prior knowledge. Another pre-activity assignment asks students to sketch free energy reaction coordinate diagrams for a catalyzed and uncatalyzed reactions (showing the catalyzed reaction having optimal binding between the enzyme and the transition state), and to list how enzymes make reactions proceed faster. The pre-activity assignments are graded for completeness only, although points may be deducted if an assignment is incomplete or extremely brief. During the in-class activity, groups work on a series of questions that explore how catalytic rate enhancement is achieved through optimal binding between the enzyme and the transition state. Ultimately, students are asked to apply their knowledge in a new situation by making statements about transition state stabilization involving metal ions and covalent bond formation. Although one activity answer sheet is collected per group and returned with instructor feedback, no points are given for group activities (except for attendance). The post-activity skill exercise, which is graded for accuracy, gives students further practice with graphing ΔG *versus* reaction coordinate by applying their knowledge to a multistep reaction. Subsequent activities are devoted to exploring Michaelis-Menten kinetics and solving real-world problems related to enzyme catalysis and kinetics. The complete activity described may be found at the POGIL website (www.pogil.org).

Typically, our course comprises a cycle of several activities, like the one described earlier, followed by one to three days of intensive problem solving. For example, in the fourth and fifth weeks of the course, three activities focus on tools scientists use to explore the structure of proteins. Two of these activities ask students to use newly acquired knowledge about protein structure and biochemical techniques to conduct mock experiments and answer open-ended questions. On the first day of this three day series, the activity has the normal structure of pre-activity assignment, in-class activity, and post-activity skill exercise. On the subsequent two days, groups are given a scenario, asked to plan experiments, and are provided descriptions of experimental results based of their planned experiments. From these mock results, groups formulate a solution that addresses questions raised in the scenario. The first day of group problem solving is for practice, whereas the second is for group points. The practice scenario is shown later. A different problem is used for group points in the subsequent class period. An example problem is given below:

> The company you work for has just isolated a protein, lakewobegonase (LWBGase), which they have found will make all women strong, all men good looking, and all children above average. To understand LWBGase and take advantage of its properties, the company wants to know something about the structural nature of the protein, immediately. The company does not have the capability of X-ray crystallography, NMR, or sequencing in house. While the company impatiently awaits the results, the CEO sends out the following memo:
>
> "The person who can get the most information about the structural nature of LWBGase in the next 24 hr will get stock when the company goes public next week, as well as a lifetime supply of LWBGase. Send all your information and data to the head honcho of the structural group for evaluation."
>
> Imagine you are in a lab conducting experiments. You have at your disposal standard biochemical reagents, an inventory of molecular weight proteins, and various chromatography and electrophoresis equipment. Design sequential experiments to collect relevant data. After each experiment contact the instructors. If your design is correct, you will receive data. When you think you have enough information, compose a memo to the CEO regarding the structural nature of this protein.

The example described above has proven very effective in helping students develop high level problems solving skills. Although the given example does not focus on a real protein, all of our concept development activities and many of our problem solving activities do. Instructors considering implementation of POGIL biochemistry could easily adapt a problem solving activity, like the one mentioned earlier, to focus on a protein of their choice.

Using Classroom Structure to Generate Positive Interdependence and Personal Responsibility

While activities extend content understanding, the course structure promotes development of critical process skills needed to achieve meaningful and long term understanding as well as important life skills in communication and critical thinking. Millis describes classroom structures as the content-free procedures that are the heart of active learning [31]. Effective structures allow the students to process the information they have explored to create meaning and commit the content to deep memory. Our course structure involves cooperative learning, which has been shown in numerous studies to advance content achievement. "However, simply placing students in groups and telling them to work together does not in itself promote higher achievement" [32]. The five essential elements of cooperative learning in groups as outlined by Johnson and coworkers [32] and described by Hanson [2] are positive interdependence, individual accountability, mutual support of learning, collaborative skills, and self-assessment. Techniques for applying these ideas for effective course structure to POGIL is available [33]. In our classroom, we assign teams, employ team covenants and roles, collect and return assignments to teams, and assign periodic self-assessment to create the positive interdependence and personal responsibility needed to achieve the critical group goals listed earlier.

In our classroom, students are assigned to teams based on information about prior grades and sociability. Diverse groups are used with a range of abilities and social skills. Although diversity is desirable, we have found that if the range is too wide, some students are intimidated and will not participate. It is important that students feel comfortable enough to "try out" an idea in order to obtain feedback from their group. Even feedback from other novices has been shown to result in deeper conceptual understanding and retention of skills over time [34]. Team covenants are created each time a new team is formed [35]. To complete team covenants, students reflect on responsibilities each individual has to their team and on the team's responsibilities to each individual. After reflecting individually, students share, discuss, and create a mutual signed document.

The team roles we use include manager, recorder, spokesperson, and reflector [1] and some less common roles including spy, skeptic, and optimist. Most teams have four individuals, with team roles rotating over the course of several weeks. The duties of the reflector, which include making observations about the team's performance, provoke anxiety for some students. Therefore, the tasks of this role are explored during an activity early in the course. The roles of spy, skeptic, and optimist are used occasionally to support the learning outcomes of a particular day. For example, the spy, which encourages eavesdropping on other teams, is a useful role when uneven performance between teams is anticipated. Sanctioned eavesdropping provides slower teams with a way to catch up and provides faster teams with an opportunity to explain their ideas [36]. The skeptic role allows one team member to question what others are saying in the team. This can be useful for improving the quality of activity answers because it forces continuous assessment. This role can also empower students who typically take a passive role in the group by giving them permission to ask questions. The optimist role is used when frustration is expected because of a challenging activity. Since negative emotions impede learning, it is important to have someone designated to find the positive aspects of the session. To foster personal responsibility and to hold individuals accountable for being prepared, all individual assignments and team activities are collected and returned in a team folder. This creates peer pressure to keep up with assignments and is cited as a motivator by students.

During class time, teams work on an instructor-designed set of critical thinking questions. Student-generated questions inevitably arise. The operational rule in our cooperative teams is that questions for the instructor must be asked by the manager, which assures that questions are from the whole team and that no team member is able to address the question [37]. Enforcement of this rule means that the expertise of the instructor is used sparingly and students gain confidence in their own abilities and the abilities of others to understand, explain and apply their knowledge. Importantly, when answering questions, instructors can promote critical thinking by avoiding authoritarian answers and instead asking students to reflect on what they know to answer their own questions. Strategies for encouraging critical thinking based on instructor answer style are described in Hanson's report on process workshops [2].

Instructor Facilitation Plans Help to Efficiently Structure Class Time

To use class time efficiently and effectively, we follow a template to create a facilitation plan [38]. The plan is created through review of recorded observations (data) on student difficulties and successes from previous class periods and from the same activity in previous years (if available). The skills that limit student learning in particular content areas are usually similar from year to year. Therefore, these data provide essential information to improve activities and advance instructor facilitation of the activity. In light of the data collected, we review the learning outcomes for the activity, the team roles needed, consider how to assess learner preparation, and create a plan to introduce the activity to the students. An essential component of the facilitation plan is to identify learning issues that may affect performance. In creating a facilitation plan, we identify the significant skills needed in order to achieve learning outcomes and describe evidence of their usage. Anticipating the skills and evidence of their use allows instructors to intervene appropriately and offer useful guidance that has been thought out ahead of time. The plan template also includes a section to be filled out after class, which prompts the collection of data during class and asks the instructor to reconcile what was planned *versus* what actually happened. This final piece provides assessment data necessary to help instructors modify their teaching plans to better meet learning outcomes in the future. Therefore, instructors have an opportunity to use the learning successes and difficulties observed one year to design strategies to improve student learning in subsequent years. Facilitation plans also help document the results of the changes.

Tools to Help Students Adapt to Active Learning

Students usually need help adapting to an active learning course. This is especially true if most of their prior coursework has been in a lecture mode. We use several tools to discover learner needs in this area and help students adapt to the course. Students begin the course by completing an activity in which they examine the syllabus [35, 39], course components (Table II), and words of wisdom offered by past students (posted at www.pogil.org). This activity provides focus for considering the general skills and content knowledge required to be successful in the course and to achieve the outcomes of the course. Furthermore, opinions from peers as presented in the words of wisdom can be helpful for social and affective issues that can impede learning [40]. When asked about the format of the course later in the quarter, students often refer to the student words of wisdom as having been formative in setting their attitude towards the course. At the end of this activity, students are given the opportunity to ask instructors any remaining questions about the course. Throughout the course, we ask reflection questions that focus on learning and also conduct a midterm assessment of the course to obtain feedback at a time when change is still possible.

EVALUATION

Student Performance

Since implementation of POGIL in our classroom, most students perform well on problems that require complex cognitive skills. In general, exam questions we ask now

Simple diffusion through the membrane exhibits a linear rate versus concentration dependence relationship whereas facilitated diffusion is saturable. Therefore, facilitated diffusion has a rate versus concentration relationship that reaches a maximum rate of transport (comparable to enzyme velocity) and further concentration increases of the molecule being transported do not increase the rate of transport.

Since we have not discussed these two situations, please construct two graphs of transport rate versus concentration,

A. one depicting the passive diffusion situation and
B. one depicting the facilitated diffusion situation.

Proteins, called transporters or permeases, transport amino acids and other small molecules across the membrane. One particular amino acid transport protein has a range of specificity for transport. Some amino acids are efficiently transported and others are not. The specificity for the amino acids was examined in an assay using radioactively labeled [^{14}C]-histidine (L-form) as the primary "substrate" for transport. The v_o values were reported as μmol [^{14}C]-histidine transported into 10^6cells/min. The K_m for histidine was found to be 10μM at pH 5.9 (the pH used for all assays performed). Other amino acids were used as competitive inhibitors of the [^{14}C]-histidine transport and the K_i values determined.

Amino Acid	K_i, μM
L-Lys	2
L-Asp	5000
D-His	340

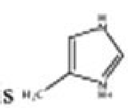
C. What do small K_i values tell you about the inhibitor? What do large K_i values tell you about the inhibitor?
D. Based on the K_i values, what are the characteristics that the transport protein prefers in the molecule to be transported?
   Compare
   1) D- and L-His
   2) L-Asp and L-Lys
   3) L-Lys and L-His. Note: R for Lys is $(CH_2)_4NH_2$ and for His is 
   Draw a conclusion about molecule preferences.
E. The K_m for histidine was found to be 190 μM at pH 6.9. What does the pH dependence of the K_m for histidine tell you?

FIG. 1. **Sample exam question used in Biochemistry 1 in 2004 and 2005.** This question was designed to test understanding of enzyme kinetics and inhibition.

are very different that those we asked when lecturing. Memorization, the cornerstone of many traditional biochemistry courses, is kept to a minimum. Exams are typically comprised 4–5 questions and reflect our high expectations for student competence. Basic facts and numerical equations are given and students are never asked multiple choice or matching questions. Instead, all questions require students to consider their knowledge in new contexts and to apply their knowledge to new problems. Clearly stating assumptions and accurately using biochemical knowledge to support their answers are two of the most important criteria considered in grading. For example, a final exam question, aimed at probing student understanding of enzyme inhibition, focused on the analogous phenomenon of transport kinetics (Fig. 1). Transport was not addressed at all in any activities, assignments, or readings and therefore is a completely new context for the students. Parts A and B of the question required students to construct plots of velocity *versus* substrate concentration and then use them in the new context of passive and facilitated transport. A correct student answer here indicates comprehension in Bloom's taxonomy for cognitive skills. Of 38 students answering this question, every student except one (97%) received full credit on these parts. Part C required students to recall the definition of K_i and interpret K_i data. 76% of students were able to correctly state how K_i data are used to dissect molecular specificity. A student who has memorized but cannot apply their information, may perform well on parts A, B and C, but could struggle with the more difficult, subsequent parts. Part D, for example, expects students to use K_i data to draw conclusions about the relevant structural features selected for by the transport protein. 54% of students scored above 83% on part D and 62% of the students earned 70% or higher. For part E of the question, students were asked to consider the pH dependence of K_m data and offer an explanation. The pK_a values for the amino acids were provided as a reference on page one of the exam, but no mention was made about that resource in the problem. 54% of students adequately drew conclusions and applied them to explain the effects of pH on the ability of the transport protein to move a particular amino acid, earning greater than 70% of total points for part E. Nearly three-quarters of the class was able to earn 70% or higher for the entire question. Although students struggled with the most abstract part of the question, we feel that overall, performance on this question was quite strong given the fact that students were asked to transpose known information to a totally new situation on an exam. In contrast to student performance on this question in our POGIL class, we have observed that most students in lecture courses are unable to perform well on exam questions that ask them to transfer information learned in class to totally new situations.

We also made a direct comparison of overall student performance in first quarter biochemistry before and after implementing POGIL at Seattle University (data not shown). This comparison, which evaluated final grades from six years of lecture and nine years of POGIL, showed more students receiving a grade of A, B, or C and fewer students receiving a grade of D, F, or W in POGIL classes when compared with lecture classes. Although such a comparison has limitations due to differences between the classes that are independent of course format, it provides evidence that student performance does not suffer under POGIL and may in fact improve. A controlled, prospective comparison of student performance in POGIL *versus* traditional classes would be required to make a definitive statement about the effects of POGIL on student performance in biochemistry. Such experiments have been conducted for general chemistry and have shown improved performance in POGIL courses when compared with lecture courses [1, 10].

Student Perception

Many students, juniors and seniors who have grown accustomed to lecture, were initially skeptical of POGIL. A review of student evaluations of teaching from 2003–2006 showed mixed responses at the end of first quarter. Although greater than 80% of students identified structural aspects course (activities, reading outlines, group problem solving, skill exercise, etc) as helping their learning, over half also asked for more lecture. By the end of third quarter, student attitudes toward the course had shifted significantly. The same percentage identified structural aspects of the course as helping their learning, but less than 20% requested more lecture. In both classes, students who had accepted our approach seemed to benefit greatly as expressed in the following quotations:

> "Working in groups in class was new, but I felt I grasped the material better than I would have from lecture."
>
> "I liked being given the opportunity to learn on my own and with other students...it boosted my self-confidence in my ability to overcome challenging obstacles."
>
> "As a whole the teaching style is very different, but in some odd way I feel better prepared for an exam the night before."

In spring 2006, we gave students a comprehensive survey, based on Elaine Seymour's SALG (Student Assessment of Learning Gains) [41], asking them to reflect on the course structure and their learning (Table III). Of those responding (24 total), 14 took all three quarters of the course and 10 took only the first and third quarters. Although the small number of respondents limits statistical analysis of the data, we believe the findings, described later, are relevant because they reflect student responses we have received in other formats since implementing POGIL in biochemistry nine years ago. In annual course evaluations, student comments support SALG findings indicating that most students feel confident in their knowledge of biochemistry after taking our class and that they believe they have received other benefits, including increased self-confidence, greater respect for others, and an ability to view themselves as scientific thinkers. Furthermore, at the end of each quarter for the past nine years, students have been required to prepare a final growth report, assessing their own development over the course of the quarter. These growth reports also support the preliminary SALG findings.

When asked about their understanding of biochemical concepts (questions 15–23), 79% or greater of students felt they understood a lot or a great deal (levels 4 and 5) of all topics except biochemical techniques (not all students enroll in lab) and additional metabolic pathways of carbohydrates, for which a high level of learning was reported by 62% and 67%, respectively. No students reported no understanding of the topics (level 1) and only a handful reported a little understanding (level 2). This high level of self-reported understanding appears to be linked to course structure. Over 80% of students agreed a great deal or a lot that the activities increased their understanding of the concepts (question 4). In addition to concept understanding, students also reported substantial gains in a variety of cognitive, social, and affective areas (questions 24–37). 92% of students thought they made major gains in taking responsibility for their own learning and respect for the opinions of others. This was rewarding since these areas represent two course goals. Around 80% of students reported greatly increased confidence in analyzing and interpreting data from the text and in their ability to learn complex material. Around 80% of students also reported gains in the ability to think through a problem and apply what they learned in biochemistry. Equally importantly, very few students

TABLE III
Student perception of learning gains in POGIL biochemistry

Number of responses at each of following levels	Levels					NA	% 4, 5
	5	4	3	2	1		
To what degree do you agree with the following statements?							
1. The readings and assignment helped prepare me for the activity	12	9	3	0	0	0	88
2. The activities helped me better understand the readings	12	11	0	1	0	0	96
3. Working with peers helped me improve how I solve problems	6	10	7	0	1	0	67
4. The activities increased my understanding of the concepts	12	8	4	0	0	0	83
5. Working with peers helped me piece together complicated problems	6	11	5	2	0	0	71
6. Feedback on activities helped me understand the concepts	2	10	11	1	0	0	50
7. Feedback on skill exercises helped me understand the concepts	6	5	12	1	0	0	46
8. The timing of the tests helped my learning	3	9	5	4	1	2	50
9. Working in groups made me less likely to give up on difficult problems	8	9	3	2	2	0	72
10. Working with peers outside of class helped me understand concepts	8	6	3	2	0	5	58
11. The way the course was taught made me more responsible for my own learning	14	4	3	3	0	0	75
12. The textbook helped me understand the concepts	7	10	5	1	1	0	71
13. Peers make the material seem more conquerable	9	6	6	2	0	1	63
14. I learn better in lecture courses	1	4	10	4	4	1	21
As a result of your work in biochemistry, how well do you think that you now understand each of the following?							
15. Amino acids and protein primary structure	10	11	3	0	0	0	88
16. Protein secondary, tertiary, and quaternary structure	12	7	4	1	0	0	79
17. Basic biochemical techniques	10	5	6	3	0	0	63
18. Proteins in membranes	5	14	5	0	0	0	79
19. Metabolism in general	9	12	3	0	0	0	88
20. Glycolysis/gluconeogenesis	12	11	1	0	0	0	96
21. Additional metabolic pathways of carbohydrates	5	11	7	1	0	0	67
22. Electron transport	9	11	4	0	0	0	83
23. Oxidative Phosphorylation	9	11	3	1	0	0	83
To what extent did you make gains in the following as a result of what you did in the biochemistry classes?							
24. Confidence in analyzing and interpreting data from the text	8	12	3	1	0	0	83
25. Confidence in analyzing and interpreting data from journal articles	8	10	4	1	0	1	75
26. Confidence in my ability to solve new problems	7	10	6	1	0	0	71
27. Ability to think through a problem	9	10	5	0	0	0	79
28. Confidence in my ability to learn complex material	11	8	4	1	0	0	79
29. Acquisition and mastery of the vocabulary of biochemistry	9	9	6	0	0	0	75
30. Willingness to ask questions of others	7	10	6	1	0	0	71
31. Ability to manage others with more expertise than myself	8	8	6	0	2	0	67
32. Becoming a self-directed learner	11	8	3	2	0	0	79
33. Becoming a self-reflective learner	8	8	6	1	0	0	67
34. Belief that I can learn and apply what I have learned in biochemistry	15	5	3	0	1	0	83
35. Tolerance of others	6	10	6	2	0	0	67
36. Taking responsibility for my own learning	11	11	2	0	0	0	92
37. Respect for the opinions of others	11	11	1	1	0	0	92

Levels: 5 – A great deal; 4 – A lot; 3 – Somewhat; 2 – A little; 1 – Not at all; NA – not applicable.

responded to any of the questions in this section at a level of 1 or 2.

Although most students self-reported substantial gains in both content knowledge and process skills, a handful of students clearly struggled with the course and vehemently demanded more lecture. Results from the survey shown in Table III indicate that students who answered question 14 with a 4 or 5, indicating that they learn better in lecture courses, also self-reported fewer gains in content understanding and process skills when compared with students who did not feel strongly that they learn better in lecture courses. Specifically, 4 of the 5 students who preferred lecture, self-reported the four lowest levels of understanding of biochemical concepts (questions 15–23). 3 of the 5 preferring lecture also self-reported the three lowest levels of gains in process skills (questions 24–37). It is impossible to know whether these students' perceived lack of achievement is due to a lack of lecture or whether their sense of accomplishment would have been equally low at the end of a lecture-based course. Also, since surveys were anonymous, we have no way to link perceived gains to actual performance. What is apparent from these findings is the importance of accommodating individual learner needs whenever possible. Although it is unreasonable to customize a class for each individual, POGIL allows for intensive student–instructor interaction and real time intervention when problems arise.

CONCLUSIONS

We have found that POGIL is ideally suited for the biochemistry classroom and results in better overall performance when compared with traditional courses. Deep understanding of biochemistry content is evident through student-reported gains and performance on difficult exam questions. Furthermore, students also report significant gains outside of biochemistry content areas, including confidence in ability to solve new problems and respect for others' opinions. We believe that these skills will benefit our students greatly in their future professional lives.

Acknowledgment— We gratefully acknowledge Jeff Stephens for his contributions in writing the early versions of many of the activities and Dan Apple for many productive conversations and support during the initial implementation. We also thank Rick Moog and David Hanson for important discussions and support throughout our development and implementation of our activities. Thanks also to Sue Jackels and PJ Alaimo for editing our manuscript. Finally we thank years of biochemistry students who have helped us better understand learning and improve our teaching.

REFERENCES

[1] J. J. Farrell, R. S. Moog, J. N. Spencer (1999) A guided inquiry general chemistry course, *J. Chem. Educ.* **76**, 570–574.
[2] D. Hanson, T. Wolfskill (2000) Process workshops—A new model for instruction, *J. Chem. Educ.* **77**, 120–130.
[3] J. N. Spencer (1999) New directions in teaching chemistry: A philosophical and pedagogical basis, *J. Chem. Educ.* **76**, 566–569.
[4] D. Hanson (2006) *Foundations of Chemistry*, 2nd ed., Pacific Crest, Lisle, IL.
[5] R. S. Moog, J. J. Farrell (2006) *Chemistry: A Guided Inquiry*, 3rd ed., Wiley, Hoboken, NJ.
[6] A. Straumanis (2004) *Organic Chemistry: A Guided Inquiry*, Houghton Mifflin, Boston.
[7] R. S. Moog, J. N. Spencer, J. J. Farrell (2004) *Physical Chemistry, A Guided Inquiry: Atoms, Molecules, and Spectroscopy*, Houghton Mifflin, Boston, MA.
[8] J. N. Spencer, R. S. Moog, J. J. Farrell (2004) *Physical Chemsitry, A Guided Inquiry: Thermodynamics*, Houghton Mifflin, Boston.
[9] M. Garoutte (2006) *General, Organic and Biochemistry: A Guided Inquiry*, Wiley, Hoboken, NJ.
[10] J. E. Lewis, S. E. Lewis (2005) Departing from lectures: An evaluation of a peer-led guided inquiry alternative, *J. Chem. Educ.* **82**, 135–139.
[11] B. J. Duch, S. E. Groh, D. E. Allen (2001) *The Power of Problem-Based Learning*, Stylus, Sterling, VA.
[12] H. B. White (2002) Commentary: The Promise of Problem-based Learning *Biochem. Mol. Biol. Educ*. **30**, 419.
[13] Dr. Kathleen Cornely Casebook. Available at www.providence.edu/chm/kcornely/Casebook.htm (revised 2006).
[14] National Center for Case Study Teaching in Science. http://ublib.buffalo.edu/libraries/projects/cases/case.html (revised 2005).
[15] W. L. Anderson, S. M. Mitchell, M. P. Osgood (2005) Comparison of student performance in cooperative learning and traditional lecture-based biochemistry classes, *Biochem. Mol. Bio. Educ.* **33**, 387–393.
[16] National Research Council, in J. D. Bransford, A. L. Brown, R. R. Cocking, Eds. (2000) *How People Learn: Brain, Mind, Experience, and School*, Committee on Developments in Science of Learning, Commission on Behavioral and Social Sciences and Education, National Academy Press, Washington, DC.
[17] National Research Council, in J. Pellegrino, N. Chudoesky, R. Glaser, Eds. (2001) *Knowing What Students Know: The Science and Design of Educational Assessment*, Committee on the Foundations of Assessment, Board on Testing and Assessment, Division of Behavioral and Social Sciences and Education, Center for Education, National Academy Press, Washington, DC.
[18] G. M. Bodner (1986) Constructivism: A theory of knowledge *J. Chem. Educ*. **63**, 873–878.
[19] National Research Council, in Pellegrino, J., Chudoesky, N., Glaser, R., Eds. (2001) *Knowing What Students Know: The Science and Design of Educational Assessment*, Committee on the Foundations of Assessment, Board on Testing and Assessment, Division of Behavioral and Social Sciences and Education, Center for Education, National Academy Press, Washington, DC, pp. 88–89.
[20] B. S. Bloom, M. D. Englehart, E. J. Furst, W. H. Hill, D. R. Krathwohl (1956) *Taxonomy of Educational Objectives: The Classification of Educational Goals. Handbook 1: Cognitive Domain*, David McKay, New York.
[21] A. E. Lawson (1995) *Science Teaching and the Development of Thinking*, Wadsworth, Belmont, CA.
[22] M. R. Abraham, in M. M. Cooper, N. J. Pienta, T. J. Greenbowe, Eds. (2005) *Chemist's Guide to Effective Teaching*, Prentice Hall, Upper Saddle River, NJ, pp. 41–52.
[23] A. E. Lawson, M. R. Abraham, J. W. Renner (1989) *A Theory of Instruction: Using the Learning Cycle to Teach Science Concepts and Thinking Skills*, National Association for Research in Science Teaching, Washington, DC.
[24] J. E. Miller, J. E. Groccia, J. M. Wilkes, in T. E. Sutherland, C. C. Bonwell, Eds. (1996) *Using Active Learning in College Classes: A Range of Options for Faculty*, Jossey-Bass, San Francisco, CA.
[25] U. Zoller (1993) Are lecture and learning compatible? *J. Chem. Educ*. **70**, 195–197.
[26] K. P. Nygren, in S. W. Beyerlein, D. K. Apple, Eds. (2005) *Faculty Guidebook: A Comprehensive Tool for Improving Faculty Performance*, 2nd ed., Pacific Crest, Lisle, IL, pp. 87–90.
[27] National Research Council, in J. Pellegrino, N. Chudoesky, R. Glaser, Eds. (2001) *Knowing What Students Know: The Science and Design of Educational Assessment*, Committee on the Foundations of Assessment, Board on Testing and Assessment, Division of Behavioral and Social Sciences and Education, Center for Education, National Academy Press, Washington, DC, p. 86.
[28] P. Black, D. Wiliam (1998) Inside the black box: Raising standards through classroom assessment, *Phi Delta Kappan* October, 139–148.
[29] C. Bergendahl, L. Tibell (2005) Boosting Complex Learning by Strategic Assessment and Design, *J. Chem. Educ.* **82**, 645–651.
[30] P. Black, C. Harrison, C. Lee, B. Marshall, D. Wiliam (2003) *Assessment for Learning*, Open University Press, Berkshire, UK.
[31] B. J. Millis, P. G. Cottell, Jr. (1998) *Cooperative learning for higher education faculty*, Oryx Press, Phoenix, AZ, p. 69.
[32] D. W. Johnson, R. T. Johnson, K. A. Smith (1991) *Cooperative Learning: Increasing College Faculty Instructional Productivity*, The George Washington University, Graduate School of Education and Human Development, Washington, DC.
[33] D. Hanson (2006) *Instructor's Guide to Process-Oriented Guided-Inquiry Learning*, Pacific Crest, Lisle, IL.
[34] S. A. Mathan, K. R. Koedinger (2005) Fostering the intelligent novice: Learning from errors with metacognitive tutoring, *Educ. Psych*. **40**, 257–265.
[35] M. Towns, in B. J. Millis, P. G. Cottell, Jr. (1998) *Cooperative Learning for Higher Education Faculty*, Oryx Press, Phoenix, AZ, p. 59.
[36] V. Minderhout, P. Smith, in S. W. Beyerlein, D. K. Apple, Eds. (2005) *Faculty Guidebook: A Comprehensive Tool for Improving Faculty Performance*, Pacific Crest, Lisle, IL, pp. 157–160.
[37] S. Kagan, in B. J. Millis, P. G. Cottell, Jr., Eds. (1998) *Cooperative learning for higher education faculty*, Oryx Press, Phoenix, p. 58.
[38] V. Minderhout, in S. W. Beyerlein, D. K. Apple, Eds. (2005) *Faculty Guidebook: A Comprehensive Tool for Improving Faculty Performance*, Pacific Crest, Lisle, IL, pp. 145–148.
[39] K. Krumseig, M. Baehr (1996) *Foundations of Learning*, Pacific Crest, Lisle, IL, pp. 23–26.
[40] A. Provitera-McGlynn (2001) *Successful Beginnings for College Teaching: Engaging Your Students from the First Day*, Atwood, Madison, WI.
[41] Student Assessment of Learning Gains. www.wcer.wisc.edu/salgains/instructor/ (copyright 1997).