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POGIL in the Calculus Classroom

Catherine Bénéteau, Zdeňka Guadarrama, Jill E. Guerra, Laurie Lenz, Jennifer E. Lewis, and Andrei Straumanis

Abstract: In this paper, we will describe the experience of the authors in using process-oriented guided inquiry learning (POGIL) in calculus at four institutions across the USA. We will briefly examine how POGIL compares to and fits in with other kinds of inquiry-based learning approaches. In particular, we will first discuss the unique structure of a POGIL activity, which includes a model and a learning cycle of specific types of questions. We then turn to a discussion of the particular characteristics of a classroom implementation of a POGIL activity, including facilitation strategies an instructor might use, the importance of specified student roles in groups, and different ways of reporting out. Finally, we provide some preliminary data on student pass rates in non-POGIL and POGIL calculus classrooms in the participating institutions. Throughout the paper, we use examples from student dialogues as groups were working through POGIL activities developed for Calculus I by the authors.

Keywords: Inquiry-based learning, IBL, active learning, POGIL, calculus, group work

1. INTRODUCTION

The dialogue below was recreated from notes from a POGIL Calculus 1 class taught at a small liberal arts university:

Hyun: We need an example of a derivative in the real world? Where neither of the variables is time? I don't know. What is an example of one in which one of the variables is time?

Kristina: Instantaneous velocity. That was the one from the drive to the cabin in the woods in the previous activity, remember?

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Hyun: Oh, yeah… Actually, no. How's that a derivative?

Kristina: Instantaneous velocity is how distance changes over time at a certain point in time. So velocity was the derivative of distance with respect to time.

Stefan (Currently assigned as **manager** of the team whose job it is to bring them together to focus on the task at hand.): Ok. So we are supposed to find an example of a derivative we may encounter in the real world, identify the independent variable and the dependent variable, and assign reasonable units to both of these and the derivative, but neither of the variables can be time… Hmm… How about temperature of a leg of deer in the oven?

Kristina: (Currently assigned as **checker** whose job it is to make sure that the group's answers make sense.) How temperature? What's the other variable? Time? Like the temperature after a certain time in the oven? How that changes?

Stefan: Yeah. It works, right?

Hyun: But we are not supposed to use time.

Stefan: Oh! Sorry. I like temperature. Can we use something else instead of time? What else can temperature change with?

Kristina: Temperature of what?

Hyun: How about a volcano?

Kristina: What else can temperature change with? We need to figure out the variable it changes with respect to.

Stefan: Distance. Let's use distance. We can have the temperature as we move away from the center of the volcano.

Kristina: Ok. So we have temperature in degrees and distance from the center of the volcano. Which one is the independent variable?

Stefan: Distance. And the dependent is the temperature.

Hyun (Currently assigned as **recorder**, whose job it is to take notes for the group): We need units.

Stefan: What should we put for units in the distance? Feet? Meters?

Hyun: Let's put meters.

Stefan: What about temperature?

Hyun: If we put meters for distance, let's put degrees C for the temperature.

Kristina (checking the group's answer): Ok, so what are we going to say our example of derivative is?

Stefan: It's the rate of change of temperature as you walk away from the center of the volcano. The units are °C per meter.

Kristina: Instantaneous!

Stefan: Oh… yeah. Instantaneous rate of change.

Hyun (writing it down): So we said our real life example of derivative is the instantaneous rate of change of temperature with respect to distance from the center of the volcano. Units: °C per meter. Ok?

Kristina and Stefan: Yes!

Hyun: Who is the **spokesperson** for the group? Oh, I'm the spokesperson today. I'll go put this up on the board.

This dialogue gives a sense of what occurred in a classroom where students were working on a process-oriented guided inquiry learning (POGIL) activity developed for Calculus I. One key characteristic of the POGIL classroom is evident in this discussion, namely, the different specified roles the students had in the discussion (manager, recorder, spokesperson, and checker). Another characteristic that is perhaps less obvious is the students' practicing certain "process skills," namely, communication, management, information processing, and critical thinking. In addition, the students are answering a question that has many possible answers and is somewhat open-ended, a question that is often referred to as "divergent" in a POGIL activity. Finally, it is evident that the students are excited about the material, operating independently from the instructor, and engaged with the mathematical content. In the rest of this paper, we will discuss in more detail how the structure and classroom implementation of a POGIL activity are specifically designed to develop these characteristics and elicit such student responses. At the end of the paper, we also discuss some preliminary grade data related to the implementations of POGIL in calculus at various institutions.

2. WHAT IS POGIL?

POGIL is one particular way of implementing inquiry-based learning (IBL). There has been much research into the effectiveness of IBL as a way to engage and stimulate student interest in a variety of disciplines, including mathematics [3, 7, 9, 11]. The authors of this paper are faculty from mathematics and chemistry, who have all used various forms of IBL or POGIL in the past. In 2011 we formed a team tasked with writing inquiry-based activities for Calculus and Precalculus that adhere to the best practices collected by the POGIL Project. The Calculus I activities are published in [13] and the Precalculus activities are forthcoming. POGIL was originally developed by a group of chemists for use in their chemistry classes. POGIL uses many of the tenets of cooperative and discovery learning, but in a systematic way that includes instructor training, peer support, and assessment. POGIL has been implemented and successfully adapted to a wide range of classroom settings, and in particular has been used in both large and small classes. Many research studies show that students using POGIL in their science classes had higher satisfaction levels, better scores on exams, and demonstrated increased retention when compared with other students taking the class in a lecture format [6, 8, 10, 14]. Other studies reporting on POGIL effectiveness can be found at http://www.pogil.org/about/effectiveness.

POGIL has two key components in the acronym: the first is that POGIL activities are developed to use a *guided* inquiry approach that uses a learning cycle of exploration, concept invention, and application, rather than open inquiry or a traditional Moore method approach; the second is the deliberate focus on developing process skills, which are skills that will not only help students to actively participate in the class, but will transfer to other contexts as well [1, 4, 12]. These skills include teamwork, management, information processing, critical thinking, oral and written communication, problem solving, and assessment. In a POGIL classroom, students work in groups of three or four with specified roles on carefully designed activities, and the instructor acts as a facilitator, rather than as a traditional lecturer. At the same time, the facilitator does need to intervene in particular ways, which perhaps differs from some other forms of IBL. In the sections that follow, we will first address the specially designed structure of a POGIL activity, and then will describe the implementation of such an activity in the classroom, using a recorded student dialogue to help describe the implementation.

3. THE STRUCTURE OF A POGIL ACTIVITY

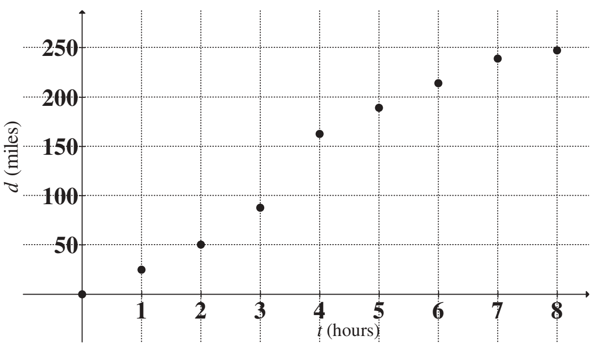
If we want our students to come out of our classes with not only thorough knowledge of the content, but also the skills that will enable them to apply these concepts to different contexts and to become more effective learners, we need to design frequent classroom or assignment tasks that develop these skills as an integral part of our courses. POGIL activities are designed to guide students through an exploration of a model that contains some new information. The model may consist of a graph, definition, picture, map, description of a real-life situation, experiment, or other item. Initial questions on the activity force the students to examine the model and help student groups construct a personal understanding of how the new information fits together, followed by questions that help students refine their understanding and come to consensus, constituting discovery of the targeted mathematical concept. This systematic approach is often called a learning cycle: exploration, concept invention/term introduction, and application [1, 4, 12]. Ideally, the exploration portion of the cycle is based on a model that builds on prior activities or is accessible to a student with no outside prior knowledge of the topic. The exploration questions are usually simple and require only a superficial examination of the model, so that students begin to develop an understanding of the model and build confidence in their abilities. The concept invention questions force the students to examine the model more carefully, think creatively, and synthesize an understanding of how the data fit together. The application questions require the students to apply the knowledge they have gained so far to similar, but different, situations, thus refining and deepening their understanding, while dispelling common misconceptions. In this section of the paper, we give some examples of models and the types of questions that reinforce the learning cycle.

3.1. The Model and Exploration Questions

The following model is the first model in the introductory activity on derivatives in [13].

Model 1: Driving to a Cabin in the Woods

A family drives from their home in the city to a cabin in the woods. Before they begin, they reset the trip odometer in their car. Then, every hour they record the trip odometer reading (the total distance they have traveled). The following graph shows the results.



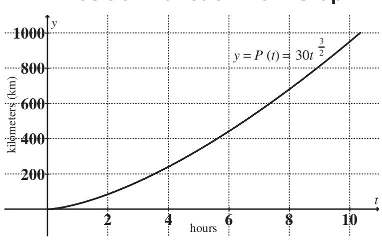
The "model" is one of the first characteristics of a POGIL activity that makes the inquiry structured in a particular way. In designing a strong POGIL activity, it is crucial to have a model that is robust, which means it needs to be accessible to the students, must contain a suitable amount of information that is often presented in different formats (above, there is both the description of the context together with a graph), and that sometimes contains comparisons that contrast situations. The authors of a POGIL activity have to choose exactly the right amount of information to give to a student, enough so that the student can understand parts of the model immediately, but not so much that you are overwhelming the student with information or giving away the whole story and removing the discovery aspect of the student's learning.

Following this model, students are asked to connect two of the points and to determine the slope of the resulting line segment. This very first question should be easy enough that students can answer it very quickly. They are then asked to describe what that slope tells them about the movement of the car during the time period. They are generally able to calculate the slope without too much trouble, but the second question forces them to really think about and examine the model, including the relevant units that they used in the first question, in order to come up with a good explanation. Another question asks them to determine the hour during which the car was most likely travelling on an interstate highway, and to explain their reasoning. This question not only helps them to examine the model more closely and to cement their understanding of what the series of points represents, but it also encourages a beginning discussion among the group members of what the slope of a line represents in a real-world situation. These questions are all examples of exploration questions where students are guided to examine different aspects of the model, but do not yet have to fully construct their understanding of a concept.

As another example, in an activity on the chain rule, the model (the third in the activity) consists of the graphs of two functions. The first function, $P(t)$, represents the position of a racecar at time t. The second function, $W(u)$, represents the tire tread thickness of the racecar's tires as a function of distance travelled (in km). These functions had been introduced in previous models.

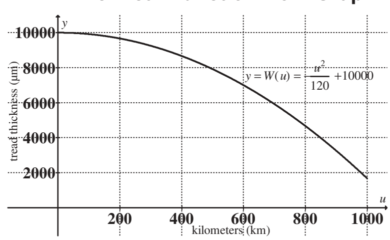
Model 3: Models 1 and 2 Revisited

Position Function from Graph I



Racecar Position as a Function of Time

Tire Wear Function from Graph II



Tire Tread Thickness as a Function of Distance.

Students are asked to describe what $P'(10)$ and $W'(950)$ represent, and to give units. This compels the students to carefully examine the input and output values for each of these functions and helps prepare them for the concept of the derivative of the composite function that comes next. The process of creating a description for these two quantities causes the students to engage with the mathematics involved. One may note that although in this question we are directing students to the particular context of a racecar, having students see some fun applications on a regular basis allows them to begin thinking about mathematics related to their own interests and to see mathematics as a part of the world around them.

3.2. Concept Invention and Application Questions in the Learning Cycle Structure

The concept invention portion of the learning cycle on a POGIL activity occurs when the students are asked to build on insights gained from thorough examination of the original model, in order to come up with their own definition or formulation of the mathematical concept that is the focus of the activity. For example, in the chain rule activity just discussed, students are asked what the product $P'(10)W'(950)$ tells them about the racecar (after they have calculated the product), where, again, P is the distance travelled by a racecar as a function of time (in hours), W is tire tread thickness as a function of kilometers driven, and $950 = P(10)$, the distance (in km) travelled by the race car after 10 hours. The question is in multiple choice format, and asks students to use units. The possible answers are: (i) tire wear per kilometer at $u = 950\text{km}$; (ii) tire wear per hour at $t = 10\text{hours}$; (iii) tire wear at a speed of 142 km/hour. Careful examination of the units is what often leads students to be able to answer this question. Therefore, students see the result of the chain rule before they have developed the formula, namely that the product of those two rates gives the rate of change of the composite function, which is the tire tread wear of the racecar during this race as a function of time, rather than distance travelled. A subsequent question gets students to connect the value they have just calculated with the slope of the tangent line of the composite function, thus leading the students to equate the two quantities and develop the formula for the chain rule.

Another example is in the introduction to derivatives activity also discussed above, where the students are comparing average rates of change:

$$v_{ave} = \frac{3t^2 - 3a^2}{t - a},$$

for values of t that approach the value a, which in this example is equal to one. First, the students are asked to use $t = 1.2$ and $t = 1.1$. They are then asked to find a value for t that would give an even better estimate of the instantaneous velocity (or speedometer reading) of the car at time $a = 1$. Finally, they are asked the question of whether their better estimate gives the very best estimate of the speedometer reading at time $a = 1$. If not, they have to describe in words how they can use the presented formula to generate increasingly better estimates for the instantaneous velocity of the car at $a = 1$ second. Students generally spend a good deal of time discussing this question. There is often one student in the group who wants to replace the value of t with one, which then leads to a discussion about division by zero, and usually culminates with the students defining the concept of the instantaneous velocity as a limit of the average velocities, the "concept invention" portion of the activity.

Once students have successfully defined the concept that was the goal of the activity, they are asked to apply this concept. The application part of the learning cycle in a POGIL activity can occur on a small scale: for example, in the introductory activity on derivatives, the students might be asked to write down the instantaneous velocity for a different function than the one presented in the model, or they might be asked to calculate that limit explicitly. Similarly, in the chain rule activity, the students might be asked to compute or interpret the derivative of a composite function for a different set of functions. This learning cycle of exploration, concept invention, and application may occur several times within an activity, in order for the students to gain a deep understanding of the mathematical concepts under study.

3.3. Questions to stimulate student self-assessment and further connections

In order to successfully guide students through the learning cycle in a POGIL activity, there are some strategies that are useful for activity writers to include. One such strategy is to include questions that require students to check their work. These are designed to allow the students to determine on their own, without needing the support of the instructor, whether they have in fact reached the correct answer for something that the authors consider crucial to the students' understanding of the topic.

For example, in an activity on continuity in [13], after the students have finished identifying points of discontinuity for a set of functions by looking at a model that consists of the graphs of the functions, they are asked the following general question about continuity:

> True or False: If $\lim_{x\to a^-} f(x) = \lim_{x\to a^+} f(x) = [\text{a real number}]$ then f is continuous at $x = a$. If false, give an example from the model that demonstrates that this statement is false, and explain your reasoning.

The very next question is a "check your work" question. It tells the students that there are actually two graphs in the model that demonstrate the statement in the previous question is false, and they are then asked to identify these two graphs. This question serves two purposes. If the students had determined that the statement was false, and had already chosen a graph that showed it, they now have to go back and find a second graph, but they are reassured that they are on the right track. If the students had answered true to the previous question, they know that their answer was incorrect and they must engage in a discussion to figure out why. They must also identify the two graphs that prove that the statement is incorrect. In either situation, the students are forced to discuss the statement with their group and to try to understand the concept more deeply.

A second useful type of strategic question that often occurs in a POGIL activity is a "divergent" question that is more open-ended, and may require information not provided in the model. (This kind of question contrasts with "convergent" questions, which usually only have one correct answer and may follow more directly from the model.) Divergent questions often occur in the application part of the learning cycle, towards the end of an activity, and they usually result in different responses from each group. For example, in the activity on the derivative at a point in [13], the students spend some time working through questions about what the rate of change would mean in the setting of a car's position or an oven's temperature at a particular time. Then students are asked a divergent question that prompts them to give an example of a derivative they might encounter in their everyday life. They are asked to identify the independent and dependent variables, and assign reasonable units to both of these and the derivative. This is precisely the question the students involved in the dialogue at the beginning of this paper were trying to answer! Students were challenged to try to find an example that does not use time as one of the variables. Students will often start out with a very vague idea for a function, one which does not actually define a relationship, such as students' grades in a class. In this case, when their peers or instructor challenged them to think more deeply and refine their idea, the students were forced to think about what variable student grades might depend on, and came up with the relationship between a student's grade in a class and the number of absences he or she had.

4. IMPLEMENTATION OF A POGIL ACTIVITY IN THE CLASSROOM: STRATEGIES FOR FACILITATION

A carefully structured POGIL activity alone is not sufficient for a successful implementation of POGIL in a classroom. Indeed, in the POGIL classroom, as in any IBL classroom, the instructor's role is to guide student learning rather than act as a content expert and provider of knowledge. Due to this shift of emphasis from an instructor-centered to a student-centered classroom, we often refer to the classroom actions of the instructor as *facilitation*. Students are expected to develop their own understanding and skills, as the instructor guides and monitors student progress. As an example of what a classroom facilitation looks like, below we include a transcript taken from a video of a group in a POGIL Calculus classroom at a large research university. The students were working on the following related rates problem, which is an application at the end of Model 1 in the Differentiation Applications 1: Related Rates activity in [13].

> Helium is leaking out of a spherical weather balloon at a constant rate of π cubic feet per second. <u>What is the rate of change in the radius of the balloon at the moment when the volume of the balloon is 33.5 ft^3</u>? It is helpful to draw a picture and you may summarize the information in a table like the one in Model 1. If you are stuck, try the next question, then come back to complete this question. Note that the volume of a sphere is given by $V = \frac{4}{3}\pi r^3$.

Description at the moment of interest: when…	**Symbol** or **Variable**	**Value** If unknown, write "?"	Units

Andy (the **manager**) calls the facilitator over to the group by raising his hand.

Andy (manager) to facilitator: We have it. We have $\frac{dV}{dt} = \frac{4}{3}\pi 3r^2 \frac{dr}{dt}$ and you simplify it and you get $\frac{dV}{dt} = 4\pi r^2 \frac{dr}{dt}$. We can't find $\frac{dV}{dt}$ and we've been trying.

Briana (reader): Seems like $\frac{dV}{dt} = 0$ which it can't be if it's like…. (she stops talking)

Facilitator: What does $\frac{dV}{dt}$ represent?

Andy (manager): The rate of change of the volume of the balloon…

Facilitator to Cathy (recorder): do you agree that $\frac{dV}{dt}$ is the rate of change of volume of the balloon? (Cathy nods)

Facilitator to Briana (reader): do you agree? (Briana nods)

Facilitator to Darryl (spokesperson): and you? (Darryl nods)

Facilitator: What would the units be for $\frac{dV}{dt}$? Do you have that somewhere? (Cathy points to her paper)

Facilitator: OK, put those units in your table. Are those units mentioned in the model somewhere?

Darryl (spokesperson): It doesn't give you enough information in the problem to answer what $\frac{dV}{dt}$ is…

Briana (reader): It doesn't tell you how fast it's going.

Facilitator: Can your reader read the question to me?

Briana (reader): It [Helium] is leaking out at a constant rate of π cubic feet per second.

Cathy (recorder): Ooooooh.

Facilitator: And what does that represent?

Briana (reader): That's just t isn't it?

Facilitator: (repeating what Briana just read) π cubic feet per second

Briana (reader): Cubic feet per second….

Andy (manager, excited): That's $\frac{dV}{dt}$!

Briana (reader) and Cathy (recorder): Yes!

Andy (manager): So $\frac{dV}{dt} = \pi$, but it's negative! (He looks at facilitator for confirmation)

Facilitator: Why would it be negative?

Andy (manager): Because the balloon is deflating.

Facilitator to the rest of the group: What do you think about that?

Briana (reader): Yeah.

Facilitator to Cathy (recorder): Do you agree? (Cathy nods)

Facilitator (pointing at the paper): So you should put in the units.

Andy (manager): What about the units for the radius? Would it be feet per second?

Facilitator: Do you mean radius or $\frac{dr}{dt}$?

Darryl (spokesperson): $\frac{dr}{dt}$.

Briana (reader): The radius.

Andy (manager): Wouldn't it be per second for the rate of change of the radius?

Facilitator: OK. What do you think? Why do you think it would be per second?

Andy (manager): Because as time goes on, the radius decreases.

Briana (reader): So the answer is $-\frac{1}{16}$!

Andy (manager): Yes!

Facilitator: Can you guys pick one row from this table in your activity, the row you're most proud of, and have your spokesperson put it on the board?

(Facilitator leaves)

Cathy (recorder): What are you most proud of?

Andy (manager, laughing): None of it!

One role of the facilitator is to create a learning environment by determining content and process skills objectives, defining expected behaviors, and establishing the team structure and reward system for the students. The facilitator must also monitor the progress of the groups and respond to questions, typically by guiding students to discuss and reflect and ultimately determine their own solutions. The facilitator also has the responsibility of making sure that groups are working as teams, and of providing closure to the lesson through various reporting out strategies.

This interaction models several of the facilitator roles described above. The facilitator is very careful not to answer any of the students' questions directly, and by using a series of her own directed questions, she guides them to refine their thinking, and they are ultimately able to come up with their own solution. She also ensures that the group is working as a team by repeatedly asking group members if they agree with one another. In addition, she hints of forthcoming closure to the lesson by directing the group to report part of their answer to the whole class. This information is combined with answers from other groups with the purpose of enabling a whole-group discussion later in the class.

One characteristic that is common to all POGIL classrooms, and to both dialogues included in this paper, is the use of structured group member roles. The roles may vary depending on the process skills that the facilitator decides to focus on, but usually, every group has a manager, who is responsible for monitoring the group's progress as a whole and for communicating with the facilitator; a recorder, who is responsible for recording group responses to questions; and a spokesperson, who is responsible for reporting out to the facilitator or to the class whenever asked. There are many other roles that instructors can use. For instance, in the dialogues in this paper, we have seen the roles of checker (who checks that the group answers make sense and are correct) and reader (who reads the questions in the activity out loud, which can help keep all members of the group working at the same pace). A facilitator might decide to assign a role of consensus builder to promote better teamwork and communication, or a strategy analyst to help the group examine the way it functions and suggest alternate problem-solving strategies. The structure of the roles in the groups forces the students to communicate whether they are the recorder, the spokesperson, or someone in the group who will be represented by that spokesperson. Everyone has some responsibility for the group's final answer. In addition, although instructors vary in their methods of selecting groups and the length of time they keep a group intact (for one unit, or for several weeks, for example), all instructors rotate individual roles, often every class, so that all students have the opportunity and the obligation to perform and develop different skills. In this way, through repeated in-class practice, students develop the ability to verbalize their questions, thought processes, and answers to each other. The relative safety and small size of the group's peer environment also allow students to communicate more freely than they might if they had to immediately provide a "correct answer" to the instructor or to the whole class.

Note that having assigned group roles is not sufficient for creating communication; one of the important interventions of facilitators is to support the students' use of the group roles. For example, in the dialogue above, the facilitator reinforced student roles by requesting that the appropriate group member perform a given task, such as the reader reading a question, or the spokesperson presenting the group's result. As another example, students who are confused or unsure will often default to raising their hand and asking a question of the facilitator instead of turning to their group to discuss the question. Some POGIL instructors address this issue by only allowing the manager to raise their hand to ask a question. It is then up to the facilitator to ensure the group has come to a consensus about their question, and that they have in fact exhausted all discussion about the topic within their group before the facilitator will attempt any sort of intervention. Many times the facilitator will merely ask them to discuss the issue some more and refine their question.

Another important function of the instructor is to facilitate "reporting out," which provides closure at important junctures and allows the whole class to come to a consensus. Reporting out is usually done by the group's spokesperson and can be done in a variety of ways, including writing on the board, writing on small white boards and showing them to the class, writing on an overhead, or even verbally reporting out answers. This allows students to share what is happening in their groups and allows the instructor to intervene and to stress or expand on certain essential mathematical content. Students are aware that a member of the group will be responsible for reporting their group's consensus to the class, which encourages more effective communication and consensus building within the group.

5. STUDENT PERFORMANCE WITH POGIL

In this section, we report the student grade distributions before and after POGIL implementation in a variety of institutions, where differences in grades were noted. Although the data clearly do not result from an experimental design, this preliminary evidence is encouraging and requires further more careful study.

Full implementation of POGIL using the current POGIL Calculus I materials commenced in the Spring 2013 semester. During this semester, four of the authors of the book Calculus I: A Guided Inquiry [13] used the activities, along with the textbook required for the class by their departments. There was some variation in the facilitation of the activities, but all instructors used all key components of the POGIL implementation, including assignment of roles and extensive reporting out strategies by students. Two of the author institutions were small, private schools with rather small classroom sizes, and at those institutions, no changes in grade distributions were noted. In the other two author institutions, one a large public research university, and the other a small, public comprehensive university, differences in grade distributions occurred.

At one author institution, the small comprehensive public university, the grade distribution from the Spring 2011 semester (before POGIL implementation) was compared to that of the Spring 2013 semester (after POGIL implementation). The ABC rate before POGIL was 60% and the DFW rate was 40%. After POGIL implementation, with the same instructor, the ABC rate was 84% and the DFW rate was 16%. The grade distribution for both semesters is given in Table 1.

At another author institution, a large public research institution, the grade distribution from the Spring 2012 semester (before POGIL implementation) was compared to that of the Spring 2013 semester (after POGIL implementation). Both sections were taught by the same instructor. Even though some PLTL (Peer-Led Team Learning) techniques were employed in the spring of 2012, the grade distributions with POGIL still improved. Before POGIL the ABC rate was 67% and the DFW rate was 33%, after POGIL the ABC rate was 77% and the DFW rate was 23%. The grade distributions for both semesters are given in Table 2.

At this university, the activities were also used in other sections, in once a week 50-minute sessions (that replaced a lecture hour) guided by undergraduate peer leaders, rather than faculty members. An extensive data analysis that examined student grade and retention data has been performed and the results are reported in [2]. These results show increased passing rates and reduced withdrawal rates for students in sections that used the Calculus I activities led by peer leaders, as compared with sections that did not use peer leading or historical data from sections prior to the intervention.

One of the concerns of any pedagogical method is its transferability from one institution to another. At times an author will have great success using her materials or pedagogical method in her own classroom, but find

Table 1. Data obtained at the small, public comprehensive university

	Before POGIL (n = 35)	After POGIL (n = 32)
Grade	Spring 2011 (%)	Spring 2013 (%)
A	14	34
B	17	19
C	29	31
D	6	8
F	23	0
W	11	8

Table 2. Data obtained at the large, public research university

	Before POGIL (n = 58)	After POGIL (n = 57)
Grade	Spring 2012 (%)	Spring 2013 (%)
A	18	27
B	24	31
C	25	19
D	18	6
F	13	15
W	2	2

that similar results are not possible in other contexts. One of the strengths of the POGIL pedagogy is that implementers have access to extensive peer-review of activities and facilitation training through POGIL workshops, which increases the chances of success in the classroom. Further information about workshops can be found at www.pogil.org/events. In chemistry and other disciplines, POGIL has been successfully used in a variety of settings; at all levels from high school to upper-level college classes, in large and small institutions, and in small classrooms and large lecture halls. The POGIL calculus materials have also been tested in many different class sizes and at a variety of institutions. The authors have held Mathematical Association of America (MAA) PREP workshops and MAA mini-courses where they have introduced POGIL to mathematics faculty who later tried the materials in their own classrooms. One participant from one MAA PREP workshop reported improvements in grade distributions in a class size of 35 at a small private liberal arts college. In the Spring 2012 semester, before POGIL implementation, the ABC rate was 60% and DFW was 40%. In the Spring 2014 semester, after implementing POGIL, her ABC rate was 78% and her DFW rate was 22%. It is encouraging to see these preliminary positive results being achieved by a non-author instructor. It would be useful to conduct a more thorough and widespread investigation of student success and retention rates for a variety of institutions implementing POGIL in Calculus I.

In addition to grade data collection, during the Spring 2015 semester, student interviews, quizzes, and classroom student video recordings were conducted at one of the author institutions to examine the question of whether student misconceptions in Calculus I, as reported in the mathematics education literature, were being addressed and mitigated by student work on the activities. Initial analysis of this data seems promising, is ongoing, and will be reported in a further publication. Enoch and Noll [5] have collected student interview and classroom recordings in non-author institutions, and reported results related to student engagement. They found that the Calculus I activities provided opportunities for students to address misconceptions but that certain group dynamics were more conducive to students engaging with the material. The extent to which the POGIL activities in Calculus I address and mitigate student misconceptions is an important question that needs further investigation.

6. CONCLUSIONS

The POGIL pedagogy gives students the opportunity to explore difficult mathematical concepts, while providing them with a safe and structured environment in which to grapple with and achieve ownership of new content. Several key aspects of POGIL promote such student learning: the activity structure based on the learning cycle, which guides students through the content; the assignment of group roles, which enables participation from all students; and the facilitation, which encourages students to take ownership of the course and their own understanding. POGIL has successfully been used in many contexts and in many different subjects and has worked well in the calculus classrooms of the four participating institutions of the authors of this paper. Initial analysis of student data, including passing rates and performance on quizzes, seems promising. Research analyzing whether and how POGIL activities mitigate student misconceptions in calculus as well as student group dynamics is ongoing.

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BIOGRAPHICAL SKETCHES

Catherine Bénéteau is an associate professor in the Department of Mathematics and Statistics at the University of South Florida, a research university with a diverse student body of over 40,000 students. Her research area is in complex function theory and she specializes in in spaces of analytic functions. She has received several NSF and other grants in the last 15 years to develop innovative inquiry-based curricula for freshman and sophomore mathematics courses and has been awarded a University Outstanding Undergraduate Teaching Award. She is a member of the Center for the Improvement of Teaching & Research in Undergraduate STEM Education.

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Andrei Straumanis holds a B.A. from Oberlin College, and a Ph.D. in organic chemistry from Stanford University. He is a co-founder of the POGIL Project, and currently serves as Consulting Scientist and Executive Editor for the Project, developing classroom materials and running faculty development workshops. He has taught organic chemistry at various institutions including, most recently, the University of Washington in Seattle. Since 1998, he has given over 100 talks and workshops on active learning and the use of the POGIL method in large classrooms. More information about Andrei is available at www.guidedinquiry.org.