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Implementation of Process Oriented Guided Inquiry Learning (POGIL) in Engineering

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ABSTRACT

This paper describes implementation and testing of an active learning, team-based pedagogical approach to instruction in engineering. This pedagogy has been termed Process Oriented Guided Inquiry Learning (POGIL), and is based upon the learning cycle model. Rather than sitting in traditional lectures, students work in teams to complete worksheets that guide them through the process of learning. The instructor's role in this class is to act as a facilitator of learning. In this way students are actively engaged in processing the information and have the opportunity to utilize and develop important skills such as teamwork, communication, and critical thinking. Assessment of this approach was conducted using formal and informal qualitative data, which revealed important elements of implementation that are needed in order to improve student learning when using this approach.

Key Words: guided inquiry, active learning, POGIL

INTRODUCTION

Teaching and learning are correlative or corresponding processes, as much so as selling and buying. One might as well say he has sold when no one has bought, as to say that he has taught when no one has learned (p. 29).(Dewey 1910)

Botany is the study of plants, not the study of books (p. ix).(Bessey 1889).

Although the lecture mode of teaching is often considered the "traditional" approach, the quotes above illustrate that "innovative" approaches to learning have been proposed for over 100 years.

Nevertheless, recently there has been an increasing awareness of the effectiveness of various types of active learning approaches. Various studies have shown that active learning leads to enhanced student outcomes compared to lecture classes (Wankat 2002; Felder 1995; Felder, Felder, and Dietz 1998; Haller et al. 2000; Demetry and Groccia 1997; Terenzini et al. 2001; Woods et al. 1997; Polanco, Calderon, and Delgado 2001; Deek, Kimmel, and McHugh 1998; Maskell 1999; Harmon et al. 2002). Prince and Felder (2006) have recently provided a comprehensive review of the effectiveness of various types of active learning methods, both within engineering and in education more generally. Their review shows that, while there may be differences depending on the type of method chosen, the experience of the instructor, and the characteristics of the students, in general active learning techniques result in improved student outcomes compared to lecture classes, particularly when deep learning is the goal. In its report *Educating the Engineer of 2020* the National Academy of Engineering explicitly calls for a focus on student-centered education (NAE 2005).

In addition to the empirical research showing improvement on various learning outcomes, the use of active learning is also supported by cognitive models of learning (Prince and Felder 2006; Svinicki 2004). These models provide an explanation for the empirical data cited above, namely that active learning approaches are more effective than lectures for deep conceptual understanding and long-term retention. Figure 1 illustrates one of these models. The key point to note in this model is that information is actively manipulated in the mind of the learner within the context of the existing structure of the learner's long-term memory. The learner has essentially three options: 1) The information can be accommodated into the existing structure. The traditional lecture approach assumes that this always occurs; 2) The new information does not fit into the existing structure, and a state

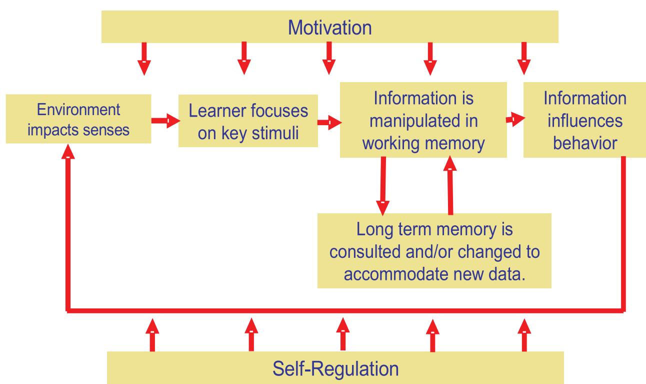

Figure 1. Schematic diagram illustrating a cognitive model of learning (Prince and Felder 2006; Svinicki 2004).

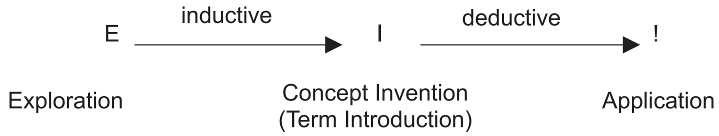

Figure 2. Schematic illustration of the learning cycle (Lawson 1995; Abraham and Renner 1986; Renner 1985).

of disequilibrium occurs. At this point the structure of long-term memory needs to be changed to accommodate the new information, or 3) The new information is rejected and long-term memory is left unchanged. As an example, Lawson (1995) describes the process by which Darwin developed the theory of evolution. Observations during his voyage to the Galapagos conflicted with his view of a Creator, leaving him in a state of disequilibrium. In order to resolve this conflict, he developed the theory of evolution.

In the classroom, this model of information processing underlies the constructivist epistemological view of learning. Constructivism states that learning occurs when learners "…think about what the teacher tells them and interpret it in terms of their own experiences, beliefs, and knowledge (Jonassen 1996)." One practical application of how to apply the constructivist epistemology is through the learning cycle model (Lawson 1995; Abraham and Renner 1986; Renner 1985; see Figure 2). In this model there are three phases of learning. The first is the exploration phase, in which the learner manipulates data or information. This results in the second phase, which is concept invention or term introduction. In this phase the learner uses the data to develop general rules or concepts. Finally is the application phase, in which the learner applies the concepts developed to new situations. This learning cycle models both the scientific research process, and the way young children learn about their world. In traditional teaching, the exploration phase is skipped, and teaching begins with concept invention. In contrast, studies have shown that learning occurs better when the concept invention phase comes later in the sequence (Abraham and Renner 1986; Hall and McCurdy 1990; Renner and Paske 1977). This approach is most powerful when the learners themselves invent the concepts (rather than having it told to them). This educational approach is the basis for constructivism. In a constructivist epistemology the roles of the instructor and students are quite different from a traditional class. Table 1, taken from Spencer (1999), compares those roles for the two approaches. In the approach used in this proposal, students work together in teams to come to a common understanding of new concepts.

In addition to the cognitive benefits of active learning, there are also opportunities for students to enhance what are known as process skills. Among these are the ability to work in teams, to communicate

Role of Instructor		Role of Student	
Traditional	**Student Focused**	**Traditional**	**Student Focused**
Lectures	Acts as consultant	Asks for the "right" answer.	Explains possible solutions or answers and tries to offer the "right" explanations. Tries alternate explanations and draws reasonable conclusions from evidence. Has a margin for related questions that would encourage future investigations.
Explains concepts	Asks probing questions of students to derive concepts.	Has little interaction with others.	Has a lot of interaction and discusses alternatives with others. Checks for understanding from peers.
Provides definitive answers.	Elicits responses that uncover what the students know or think about the concept.	Accepts explanation without justification.	Is encouraged to ask questions such as, Why did this happen? What do I already know about this? Is encouraged to explain other students' explanations.
Tells the students they are wrong or right.	Provides time for students to puzzle through problems.	Reproduces explanation given by the teacher/book.	Tests predictions and hypotheses. Uses previous information to ask questions, propose solutions, make decisions, and design experiments.
Explains to students step-by-step how to work out a problem.	Allows students to assess their own learning and promotes open-ended discussion. Refers students to the data and evidence and helps them look at trends and alternatives. Encourages students to explain other students' concepts and definitions in their own words.		

Table 1: Comparison of instructor and student roles in traditional and constructivist models.(Spencer 1999)

effectively, and to be able to assess their own work. The Accreditation Board for Engineering and Technology (ABET) in the US has formalized the need for these skills by explicitly including them among the outcomes required of engineering graduates, and in response many (if not all) engineering programs have sought ways to integrate these skills more completely into their curricula. Similarly the EUR-ACE Framework Standards for the Accreditation of Engineering Programmes requires the development of teamwork, communication, and life-long learning. The approach used here allows students to access these skills through its emphasis on students working together in teams as they go through the learning cycle. During this process, the students must communicate with each other and the instructor, and assess their own knowledge and understanding as they come into conflict with the knowledge and understanding of other students during the team discussion.

In addition to these professional skills, there is a need to develop in students the skills of information processing, analytical reasoning, and problem solving (or more generally, the ability to think critically) in order to function as practicing engineers. Various authors have pointed out how problem-solving is at the core of engineering practice (Denayer, Thaels, Vander Sloten, & Gobin, 2003; Winkelman, 2009; Mourtos 2004; Simon 1981). Within the context of Bloom's taxonomy for the cognitive domain (Bloom et al. 1956; Anderson and Krathwohl 2000) this corresponds to operating at the higher levels of Analysis, Synthesis, and Evaluation (or Analyzing, Evaluating, and Creating in the 2001 revision). In contrast, other than the capstone design course, most engineering courses have traditionally operated at the lower levels of Knowledge, Comprehension, and Application (Wankat 2002). The ability to engage in higher order thinking is in many ways entwined with the active learning approaches described above; when students are actively engaged with trying to make sense of information, they must utilize those higher order skills in order to process that information and fit it into the context of their existing mental structure. Several studies have shown that inquiry-based classes promote development of reasoning skills; while most have been at the secondary level (Gerber, Cavallo, and Marek 2001; Linn and Thier 1975; Purser and Renner 1983), a few have been conducted on college students (Johnson and Lawson 1998; Renner and Paske 1977).

PROCESS ORIENTED GUIDED INQUIRY LEARNING

The materials described here are based upon the approach developed as part of the larger POGIL Project. A number of textbooks are now available for the chemistry curriculum based on the work of the POGIL Project (Moog and Farrell 2002; Straumanis 2004; Spencer, Moog, and Farrell 2004; Moog, Spencer, and Farrell 2004) and a POGIL text for materials engineering has been recently published by the first author (Douglas 2014). Elements of the POGIL approach also exist within other approaches such as cooperative and collaborative learning (Wankat 2002; Felder 1995; Felder, Felder, and Dietz 1998; Haller et al. 2000; Demetry and Groccia 1997; Terenzini et al. 2001), problem-based classes (Wankat 2002; Woods et al. 1997; Polanco, Calderon, and Delgado 2001; Deek, Kimmel, and McHugh 1998; Maskell 1999; Harmon et al. 2002), and guided design (Wankat 2002).

In a POGIL classroom, the instructor does not lecture. Rather students work in teams, typically of four students, to complete worksheets. The worksheets contain three components: 1) Data or information as background material; 2) Critical thinking questions, which are designed to lead the students to understanding the fundamental concepts represented by the data, and 3) Application exercises, which provide the students with practice in solving problems using the concepts they have derived. The instructor's role is to guide the students, walking around the room and probing them with questions to check their understanding (Farrell, Moog, and Spencer 1999; Hanson and Wolfskill 2000). Farrell, et al. (1999) have described the roles of students within the groups and the class procedures. Typical roles are Manager (responsible for ensuring that tasks are completed), Scribe (records the groups answers), Presenter (presents group answers to the class), and Reflector (observes and comments on group dynamics) or Technician (the only person allowed to operate a calculator). The typical class period proceeds as follows:

1. Instructor posts team assignments and roles for that day. Teams will typically stay intact for several class periods, although roles will change each day.
2. A brief recap of the previous day or an introduction to that day is given by the instructor. This is where students can be motivated by describing engineering applications of the concepts or demonstrations can be presented as a "teaser" for the day's activities.
3. Students begin working on the day's activities.
4. The instructor observes the groups and may interact with them in several ways. He may respond to questions from a particular group, or may ask questions of particular members of a group. This latter technique is particularly useful if it appears that one member of a group is lagging behind the other members in understanding.
5. If a particular question is causing difficulty for several groups, the instructor may choose to interrupt all groups, and have the presenters from each group discuss their group's answer. In this way, different approaches can be compared and a consensus answer obtained. The instructor may also stop the class to clarify concepts as needed.
6. Throughout the class the instructor may build in deliberate stopping points. These stopping points serve several purposes. By announcing that groups should reach a certain question after a specified period of time, they serve to keep the groups moving through the questions so they do not get bogged down and fall behind. They also serve as points where Concept Checks (clicker questions) can be asked to ensure students understand the material to that point before moving on (see below and Table 2 for more details.)
7. With about 5 minutes left in class the instructor stops the activity. He may summarize the day's activities himself, or ask the presenters to present some aspect of their group's work as a means of providing a summary.
8. Students are then given a brief period of time to complete a Scribe Report in which they reflect on their group's performance (see below and Table 2 for more details).
9. Students are not expected to do reading before class, since the learning cycle asks them to develop the ideas for themselves. After class they may do reading on their own. They also are given homework which allows them to practice using the concepts developed in class.

POGIL Component	Description	Aspect of Learning
Background	Introductory material that describes potential applications or importance to engineering.	Motivation
Model	Data for the students to explore.	Exploration
Guided Inquiry – Directed Questions	Questions that direct students to specific aspects of the model.	Exploration
Guided Inquiry – Convergent Questions	Questions that guide students to developing a concept.	Concept Invention
Guided Inquiry – Divergent Questions	Questions that have students expand concepts in new ways.	Application
Concept Checks	Clicker questions to check student understanding during class.	Application
Exercises	Homework problems that directly apply concepts.	Application
Problems	Homework problems that apply concepts in new ways.	Application
Scribe Reports	Reflections by the group on their performance in that day's class.	Self-Regulation

Table 2: Components of a POGIL class, and their relationship to elements of the cognitive model of learning (Figure 1) and the learning cycle (Figure 2).

The worksheets themselves are carefully designed to follow the learning cycle. They consist of the following elements (see Table 2 for a summary):

Background Material: The worksheets begin with information that describes potential applications of the concept or their importance to engineering. The purpose of this background material is to motivate the students by providing them an orientation as to why the concepts are important. Often this can take the form of an every-day application with which they are familiar. (E.g. The composition of lead solder is 60 wt% lead and 40 wt% tin. Why is that specific composition used?)

Model: This may be a figure, graph, table, or demonstration.

Guided Inquiry Questions: These questions guide the students to an understanding of the concepts in that particular activity. Each activity contains three types of questions. *Directed questions* focus the students' attention on specific aspects of the data, and the answer is found directly in the Model. (E.g. What is the composition of the metallic alloy shown in the Model?). *Convergent questions* help the students to bring together the data to come to a general conclusion or understanding of the concepts. The answer is not directly available from the Model and requires analysis and synthesis. (E.g. Based on your answers to questions 1-5, how does the strength of a single phase alloy change as the composition changes?) *Divergent questions* are open-ended questions that ask the students to expand on their new knowledge by pondering, further exploring, and generalizing. (E.g. Which is more effective at strengthening aluminum, solid solution strengthening or precipitation hardening? Justify your answer on the basis of technical and/or economic considerations.)

Concept Checks: Concept Checks are questions that are used during the class period to check student understanding. One effective way to use these questions is with personal response systems ("clickers"). Clickers allow the instructor to quickly see if the students understand the concept. If a majority of the class gets the question correct, students can move on to the next set of questions. If many of the students get it wrong, the material can be reviewed. The students would then be given a second opportunity to answer the question.

Exercises: These are straightforward homework problems that ask the students to apply the specific concepts they have learned in ways similar to what was developed in the Guided Inquiry Questions. (E.g. For each of the following alloys, identify which is the strongest, and explain why.)

Problems: These are higher order thinking homework problems that ask the students to apply the concepts in new and unfamiliar contexts. Often these will be "real world" problems. (E.g. Using data from your text, determine if it is possible to create a Cu-Ni alloy with a minimum strength of 300 MPa and a minimum ductility of 40%. If it is possible, identify the composition of the alloy. If it is not possible, explain why.)

Scribe Reports: These are separate from the worksheets, but are an important aspect of the class. The student groups are prompted to reflect on their performance in that day's class by answering questions such as: What was the most important thing you learned today? What question do you still have about the material? What was a strength of your group's performance? What could be improved about your group's performance?

Most important to note is that the steps used to complete the worksheets follow the constructivist learning cycle, and that students must access a variety of process skills while they are completing the worksheets.

EXAMPLE POGIL LESSON

Examples of the different phases of a POGIL lesson are described in this section, illustrating each aspect of the process described above. This lesson is for the core engineering course Introduction to Materials. Students in this course range from sophomore materials science and engineering students to graduating seniors in other engineering disciplines. This particular lesson comes approximately midway through the semester, and is the first in a series of lessons on phase diagrams. The specific lesson objectives for this class are:

- Define the terms "phase" and "component".
- Given a mixture of substances, identify the phases and components present.
- Define solubility limit.

In a traditional (non-POGIL) lecture class, the first two lesson objectives are typically covered in a lecture format; the instructor provides the definitions and then gives a few examples. The approach taken in this POGIL class is essentially the opposite. The class begins with the instructor providing a model, as shown in the following video:

http://download.mse.ufl.edu/douglas/initial_information.mov

As can be seen in this video, there is no explanation given as to the phases or components in these mixtures. After seeing this model, the students answer the following series of questions, working together in groups as described above:

1. In the solution of sugar completely dissolved in water, what substances are present?
2. In the solution of sugar completely dissolved in water, what states of matter are present?
3. In the solution of sugar partially dissolved in water, what substances are present?
4. In the solution of sugar partially dissolved in water, what states of matter are present?
5. For a mixture, can you predict the number of states of matter present by knowing the number of substances present? Explain your answer.
6. In the mixture of water and oil, what substances and states of matter are present?
7. What is different about the mixture of water and oil compared to pure water or pure oil?
8. Is listing the substances and states of matter present sufficient to describe a mixture? Explain why or why not.

The purpose of these questions is to force the students into a state of disequilibrium in terms of their understanding of the term "state of matter". They must confront the dilemma that both the solution of sugar fully dissolved in water and the mixture of water and oil are one state of matter, liquid, and yet there is something fundamentally different about those two mixtures. The students are then given the following model:

Sugar completely dissolved in water has two components and one phase.
Sugar partially dissolved in water has two components and two phases.
A mixture of oil and water has two components and two phases.
Solid sugar has one component and one phase.
Pure water has one component and one phase.

Based on this model they then answer the following questions:

1. Based on the mixtures and the information provided above, provide a definition for the term "component".
2. Based on the mixtures and the information provided above, provide a definition for the term "phase".

The following video shows the students working together to answer the questions. Note the role of the instructor during this video:

http://download.mse.ufl.edu/douglas/group_work.mov

In this part of the class the instructor is acting as a facilitator, and for the most part is simply observing the groups. In one instance he intercedes when he notices that the group's answer to question 2 is not consistent with the model. Note that he does not provide the answer, but just points out the inconsistency and then leaves the group to work out the answer.

It can also be desirable at times for the instructor to conduct a whole class activity, especially in large classes where it is not possible to monitor all the groups. This activity can take several forms: the instructor could give a "just-in-time" mini-lecture on the topic; several groups could be asked to give their answers to a question and explain their reasoning; or the Presenter for one group could go to the blackboard to show how they solved a problem. A discussion can also serve to clear up any misconceptions that remain. The next video shows a discussion of the definition for the term "phase". The definition developed by the students at this point is that the solution should appear uniform to be a single phase. A student then asks if you can transform the oversaturated solution from two phases to a single phase by mixing it so that the sugar particles are floating in the water, thus making the liquid appear uniform. In the video the students discuss additional criteria for when a liquid is one or two phases:

http://download.mse.ufl.edu/douglas/class_discussion.mov

The goal here is not necessarily for the students to know the exact textbook definition. Rather, what is important is that students have an understanding of the concept of "phase", and can apply it to various situations. This understanding is then tested with "clicker" questions in which they are asked to identify the components and phases in various mixtures.

ASSESSMENT RESULTS

The effectiveness of POGIL at improving student outcomes (primarily measured through grades) has been reported previously (Farrell, Moog, and Spencer 1999; Hanson and Wolfskill 2000). Here we focus on qualitative assessment to understand what elements of the class either helped or hindered student learning, with the goal of understanding how to improve implementation of the POGIL approach. Data was collected in three different semesters in which the first author taught the class using POGIL: fall 2008, spring 2010, and spring 2012. Data consisted of formal and informal interviews conducted by the second author, and excerpts from scribe reports. Formal interview questions included, “How does your group work together?”; “What do you think of the worksheets?”; and “How does this class compare to your other engineering classes?” Data was analyzed by grouping statements into themes reflective of how various aspects of the class affected student learning. Four broad themes emerged from the interviews.

The first theme identified was that students did recognize the benefits of working in groups, such as promoting critical thinking, learning cooperative skills, gaining different perspectives, and retaining content knowledge. The diversity of engineering majors in the same group provided opportunities for each student to contribute their own input, resulting in the group being able to solve the problems together. One student, Long (all names given are pseudonyms), described his group experience, “the group members kinda had diverse backgrounds, I mean some of us were chemical and other were more physics-based, so a lot of the questions we figured out ourselves.” The students’ understanding and learning were deepened and enhanced by group discussion. For example, Chris stated, “From our group session, well, they’re interesting people and also, they can figure out stuff that I can’t, so it is pretty helpful so I miss some stuff and then we can get together, figure it out.” However, some students also reflected that group dynamics had an influence on the quality of group discussion. A good group rapport took time to establish. Once the students were more accustomed to getting into groups, they felt more comfortable working with others. Ultimately, the way the group operated was seen as a key to success in the class, as described in one scribe report: “With this style of class, the quality of the education you receive is directly related to the amount of effort your group puts forward. Without reflecting on your group’s performance, it is incredibly easy to fall into a pattern or routine that creates ‘blind spots’ in your knowledge of the material. Because of the way this class builds upon its material from lesson to lesson, if your group does not catch potential weak spots or areas for improvement quickly, their negative effects will compound and require much more effort to correct in the future.”

The second theme was that the use of worksheets increased students’ levels of understanding of the content and their engagement. During group discussion, the students had to be actively involved in the problem solving process and interact with their group members rather than sitting and listening to lectures. One student, Sanjay, identified that the worksheets helped most in this guided inquiry class with the statement, “the questions on the worksheet were so, like common sense that they were like, ‘Oh, why is he asking us this?’ But it actually helped us better understand the concepts that he was trying to explain." Some students acknowledged the benefits of the worksheet to engage them better in discussion. Lamar stated, "Since we had the worksheets to guide us, the worksheets helped us to keep focused working in group."

The third theme was that the use of guided inquiry in this setting had minimal benefit for some students due to their expectations for what constitutes an engineering class. Some students felt uncomfortable with not being told the answers to the worksheet questions and suggested that the instructor offer the answers to all the questions so they knew they were getting them correct. One student, David, shared his experience in guided inquiry learning, "Well sometimes yeah we do get to those questions where we can't find information or we don't know exactly what to put down so we talk about it for a little while and then we pretty much decide to wait till the professor stops, so we can make sure for right or wrong." Even though the instructor provided an active learning environment, students still expected to be fed knowledge by their instructor. Long expressed his concern in the interview, "I don't want the worksheet to completely take over and just feel like I'm – I'm never really getting taught by someone." A related issue is that some students did not seem to recognize the need to engage in critical thinking to answer the questions. However, other students seemed to recognize that they could use the worksheets to develop their own understanding of the material. One group's scribe report stated, "We are not so accepting of the answers to the questions as we would be if a lecturer was feeding us the material. As a result, everyone is more alert, and more ready to think through the problem before accepting the first answer and moving on." This quote particularly shows how the students in this group have developed critical thinking skills through the use of POGIL. The Concept Checks (clicker questions) were also seen as an effective way to gauge learning, with one student stating, "Sometimes you are not sure if you understood the concept, but if you get the right answer on the concept check, then you are sure you got it."

The final theme was the description of specific strategies that students developed to help them in the class. Some strategies identified by students and on Scribe Reports were: having the manager make sure everyone understood the answer before moving on; using a stopwatch to keep track of time in class so they finished the material for the day; and having the manager inform group members when they had to answer a Concept Check (clicker question). One group's scribe report described why they had decided to look at the worksheets before coming to class: "We all read over or skimmed the lesson about unit cells before we got to class. Although we might not have understood what was in the text before, we came in with some background knowledge that helped us when we were doing work. This allowed us to have more time to discuss our answers and explain things to each other better." Their goal was not to fully understand the material before coming to class, but to at least have thought about it so they were prepared for discussion with their group members.

CONCLUSIONS

This paper describes implementation of process-oriented guided inquiry learning in an engineering classroom. The goal of this class is to reverse the pedagogical roles of the instructor and the student, making students responsible for constructing their own understanding of the material and leaving the instructor to serve as the facilitator of this learning. While this paper provides one specific approach to accomplishing this goal, there are various other active learning approaches that may also be appropriate depending on the specific context of the class.

The assessment results suggest that a number of factors must be considered when implementing POGIL. The traditional classroom that students experience throughout their education sets up certain expectations that the POGIL instructor must be careful to manage. The primary expectation that seems to be revealed from the assessment is that students expect to be “taught” by an expert. Thus, it is important that appropriate feedback is provided so that students have a sense that the instructor is a part of their learning. Giving rationales and starting a whole-class discussion about the implementation of POGIL will help them make sense of their own learning and increase their awareness of being an active learner. At the same time, however, the instructor must be careful to guide the students in ways that still lets them discover the concepts on their own and promote their accountability. Thus, there is a delicate balance that must be maintained in order to make POGIL effective. For instance, providing students opportunities for self-assessment of their learning in class through Concept Checks and Scribe Reports is a possible way to accomplish this.

Additional work is clearly needed to demonstrate how to best use POGIL within engineering, as well as to understand how learning occurs in the POGIL classroom. We are currently analyzing qualitative data in detail using contructivist grounded theory, which will provide an in-depth understanding of the processes students used. We expect the theory that develops will be useful for developing more detailed guidelines for the use of POGIL.

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