Use of POGIL Methodology in Undergraduate Mechanical Engineering Courses

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ABSTRACT

Process-Oriented Guided Inquiry Learning, or POGIL, was first developed in the early 1990s as a method for improving the understanding of introductory undergraduate level Chemistry classes and proved to provide a significant increase in the percentage of students who mastered the course materials. POGIL has since expanded to be used in a wider variety of STEM classes, but, to the author's knowledge, no professor has tried using POGIL in undergraduate Engineering Thermodynamics, Fluid Mechanics and Heat Transfer classes. This paper will provide an overview of the POGIL approach, which uses small teams of students to explore concepts and solve problems with the instructor acting as a facilitator. It will also report on the results of an initial use of POGIL in Hanover College Engineering classes. These results will be compared to the results from the previous offering of the same courses which used a traditional lecture-based approach. To minimize other potential influences on the student outcomes, the author was the instructor in each of the classes. In addition to looking at student outcomes such as grades and student course evaluations, the paper will also share examples of the POGIL exercises worked on by the student teams.

Introduction: What is POGIL and Why Use It?

According to the website of the POGIL Project, POGIL is "a student-centered, group-learning instructional strategy and philosophy developed through research on how students learn best".[1] The pedagogy revolves around students working in groups of three or four to discuss and solve problems specifically designed to mimic "the processes of research and discovery".[2]

POGIL has two principal goals: "improve content mastery" and "helping students develop important life and learning skills".[3] The latter goal is part of the "process-oriented" approach.

In their small groups, which take place during normal class time under the guidance of the instructor, each student has a specific role to play such as manager, notetaker and researcher. These roles can help prepare students for roles they will fill at various points in their careers when working on project teams. Among the process-oriented skills POGIL is designed to promote are: oral and written communication, teamwork, information processing, critical thinking, problem-solving, management, and assessment.[4]

However, it is the mastery of content that has been the primary motivation for implementing POGIL. What is now known as POGIL was started by Franklin & Marshall College Chemistry professor Richard Moog in the early 1990s. He was frustrated by the lack of success of so many of his students that he

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[1] https://pogil.org/about-pogil/what-is-pogil, accessed January 2022.
[2] Simonson, S.R., editor, POGIL, Stylus Publishing, 2019.
[3] Ibid.
[4] Ibid.

decided he needed to change his teaching strategy. The change he made was from "instructor-centered based on historical precedent and practice to a student-centered approach based on research on learning".[5]

In addition to each student playing an assigned role, a typical POGIL "activity" or breakout is meant to be the first introduction to new material. It is assumed that students have not encountered the material before the class session. Also, the activity is expected to be completed during the class session with occasional hints and suggestions from the instructor. It is not homework, but homework can also be used to reinforce the learning.[6]

Perhaps the easiest way to explain POGIL is via an example of a POGIL activity. Appendix A contains a POGIL activity created by Clif Kussmaul, a former member of the Muhlenberg College Computer Science faculty. He has used it in his classes as way to introduce students to the POGIL process and to gain buy-in from the students that the process will be beneficial to them.

Several takeaways from Kussmaul's example are worth noting:

- The activity begins with a presentation of data – this mimics the research and discovery process
- Many of the questions seem overly simple and have obvious answers – this is intentional and is meant to help the students fully explore the data before jumping to conclusions while also getting everyone on the same page
- The previous questions tend to lead the students to the answer to the final question (#4 in the example) – this is what is meant by "guided inquiry"

Kussmaul's example also provides data on the impact of using POGIL in the classroom. In 2019, Stanley Lo and Jonathan Mendez reviewed published data on the impact of POGIL on student learning.[7] They drew from 43 studies that had reported results from using POGIL in normal classroom settings. Most of the studies were from undergraduate courses and all but eight were from STEM-related courses. Only one of the 43 studies reported worse performance by students in a POGIL class compared to a non-POGIL class and 79% of the studies reported improved performance. The median improvement in GPA, based on a 4-point scale, was 0.47.

Initial Use of POGIL by a Novice in Introductory Material Science Class

The author's first attempt at teaching an introductory level, elective course on Materials Science (ENGR 207) followed the "sage on the stage" methodology with lectures for one hour and 45 minutes once a week and weekly homework assignments based on problems drawn from a widely used textbook.[8] Despite trying to keep students engaged by drawing on examples the author had gained from interacting with materials experts during 30 years of industrial experience, most of the students simply did not grasp the concepts sufficiently to do well in the course. The final grade distribution was bifurcated with five of 14 students getting an overall average of 88% or better while five got an average of 75% or less, and one withdrew before the mid-term exam.

After the experience of teaching ENGR 207, the author concluded that the majority of today's generation of students do not respond well to the methods that were used in Engineering classrooms in the 1980s when he was a student. However, with little time to make modifications in his planned approach for the

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[5] Ibid.
[6] Ibid.
[7] Ibid.
[8] Jones, D.R.H., and M. F. Ashby, Engineering Materials 1, 5th edition, Butterworth-Heinemann, Elsevier, 2019.

follow-on Materials Science II (ENGR 208) course, a decision was made to continue using the traditional pedagogy in ENGR 208 which was offered in the winter 2020 semester.

Most of the students who struggled in the first Materials Science course, did not register for ENGR 208. (Both courses are electives, so ENGR 207 students were not compelled to continue in 208.) However, that meant only six students were in the follow-on course. When many of those stronger students did poorly on the mid-term exam, the author realized a change in teaching strategy was needed.

While describing to a colleague in the Computer Science faculty the author's challenge of trying to keep students engaged in an hour and 45-minute Material Science session, that colleague recommended trying to use some POGIL activities. After doing some research on the POGIL Project website, the author discovered that Douglas[9] had written a textbook on Materials Science for Engineering that incorporated the POGIL methodology and included multiple POGIL activities in each chapter. The author reviewed a copy of the textbook and decided to adapt a few of the activities in the second half of ENGR 208 as a trial run. The adaptation mainly required modification of the nomenclature to match that of the Jones and Ashby textbook. Shortly after starting to incorporate POGIL exercises into the class, the author's institution moved to fully on-line instruction due to the rise of the Covid-19 pandemic. By using the break-out rooms feature in Zoom, the team-based POGIL activities worked surprisingly well in an on-line environment. The class had six students, so they broke into two groups of three to have private discussions and then returned to the full Zoom session after five or ten minutes to share their conclusions. For the end of course evaluations, the students were specifically asked to comment on the use of POGIL. Five of the six students submitted anonymous evaluations. All their POGIL related comments are listed in Table 1.

Table 1 – POGIL-related Comments from ENGR 208 Materials Science II Student Evaluations (Winter 2020)

Student Responses to "What aspects of the course did you find particularly effective?"
I really liked the guided inquiries. It allowed me to practice examples in class and made the homework more understandable.
The guided inquiry's problems were really effective to work on what we have learned in the class.
The in-class participation.
Student Responses to "What course improvements would you suggest?"
Use guided inquiries throughout the entire semester. Maybe even use them in 207.
Student Responses to "Please provide comments about the aspects of REMOTE learning that were the most effective for your learning"
Breaking the class into different rooms when answering the guided inquiries was very effective.
I liked the guided inquiry sessions, and I think they really helped me to learn the material.

In addition to the positive feedback on the use of POGIL during the second half of the course, all students received at least a C in the course and no student withdrew from the course during the semester. This was

[9] Douglas, E.P., "Materials Science and Engineering: A Guided Inquiry", Pearson, 2014.

a meaningful improvement from the first Materials Science course in which roughly 20% of the students either received a grade less than C or withdrew during the semester. However, since all of those students who did not do well in 207 did not continue in 208, it was too early to declare the use of POGIL a success.

Expanded Use of POGIL in Mechanical Engineering Courses

During the summer of 2020, the author participated in an on-line Fundamentals of POGIL workshop offered by the POGIL Project. This workshop provided insights into the importance of having students play different roles in their break-out groups while solving problems. The workshop also gave valuable tips on how to be an effective facilitator while the students are engaged in POGIL activities.

<u>Instrumentation & Statistics</u>

Strengthened by the knowledge gained from the workshop, the author decided to incorporate some POGIL activities into a fall 2020 class on Instrumentation and Statistics (ENGR 321). The course was taught face-to-face for the first 10 weeks, and then was switched to virtually classes for the final four weeks of the term. The textbooks used for the course were a comprehensive open-source reference on industrial instrumentation written by Kuphaldt[10] and a Statistics textbook from the "OpenIntro" series.[11] Neither textbook included POGIL activities, so the author developed one or more POGIL activities for each class session – often drawing from example problems found in the textbooks. While many of the activities likely do not qualify as "official" POGIL activities because they do not strictly follow the "model-conceptual questions-application questions" methodology, the author still referred to these as "POGIL exercises" in class and required the students to play one of four roles:

- Manager – read the POGIL handouts, kept the group on task
- Researcher – only person allowed to use a calculator or search the internet
- Communicator – only person allowed to communicate with the professor during the breakouts and also reported results out at end of breakout
- Timekeeper/Process Observer – watched clock to ensure group finished on time, also checked to ensure everyone was understanding how the answer was obtained

These roles were assigned via a random number generator function in Excel at the beginning of each class so that students had to play different roles throughout the semester.

A typical ENGR 321 class with POGIL consisted of:

- A 10-15 minute slide-based lecture that introduced a concept or theory
- A 15-20 minute POGIL session giving students an opportunity to explore the concept and apply it
- Another 10-15 minute slide-based lecture introducing another concept of theory
- A second 15-20 minute POGIL session exploring the second topic

The author found the most challenging aspect of using POGIL activities was to accurately estimate how much time it would take students to work through the activities and find answers. Rarely was the necessary time over-estimated, but there were often underestimates. Questions related to concepts were the ones that tripped up students more often than application-oriented questions, which is not unusual for

[10] Kuphaldt, T., "Lessons In Industrial Instrumentation", version 2.32 (available for download at: https://www.ibiblio.org/kuphaldt/socratic/sinst/)
[11] "OpenIntro Statistics" by Diez, Barr and Cetinkaya-Rundel, 3rd edition (available for download at: https://open.umn.edu/opentextbooks/textbooks/openintro-statistics)

Engineering students. However, the underestimating of time requirements meant that, overall, less material could be covered in the course compared to the previous time it was taught using traditional lecture-only methodology. This is a common outcome that has been reported by POGIL practitioners.[12]

Due to the small number of students in the fall 2020 course compared to the previous offering of the course, it is not appropriate to claim a statistically significant improvement in student performance.

Fluid Dynamics

The author continued to incorporate POGIL activities into courses during 2021. First, in the winter 2021 semester, was a Fluid Dynamics course (ENGR 336), which was taught entirely face-to-face. Using the same textbook he had used in the previous offering of the course[13], the author developed 31 POGIL activities that were used to augment the lectures used in the previous course. Again, estimating the amount of time to allocate for each activity proved to be a challenge, and this meant less material could be covered during the semester. However, the author intentionally spent one less day reviewing material that was introduced in the pre-requisites for the course, so the total amount of new material that was not covered in the POGIL version of the course was no more than what could have been covered in two full 70-minute lectures.

While the student evaluations unanimously cited the POGIL activities as an aspect of the course that was “particularly effective”, the small number of students in the course (four) makes it difficult to draw statistically meaningful conclusions on student performance.

Thermodynamics

The next course in which POGIL was incorporated was an Engineering Thermodynamics course (ENGR 339). The first time this course was taught in 2019, the author found it to be particularly challenging because it was offered as a 4-week intensive course during his institution’s May term which meant that the class met every day for approximately two and half hours. Other May term classes have a reputation of being “easy” or “fun”. In addition, there are many extra-curricular activities that occur on campus during May term that can serve as a distraction to studying.[14]

In an attempt to counteract the factors that could cause students to lose interest, the author developed more than 30 POGIL activities. As was the case with ENGR 336, a non-POGIL-based textbook was used[15]. The POGIL activities were interspersed with short lectures that either introduced or reinforced the concepts covered in the activities. One activity is shown in Appendix B. It was used to introduce students to the concept that the second law of Thermodynamics shows us that heat can only flow from a hotter location to a colder location. To flow in the opposite direction would be a violation of the second law. A particularly important part of the activity was not just to have the students obtain a numerical result, but to also explain how they obtained their answer.

The course was taught entirely face-to-face, and all six students in the spring 2021 class responded to the anonymous course evaluation. POGIL-related comments from the evaluations are listed verbatim in Table 2. In addition to the generally positive student reception of the POGIL activities, student academic performance was also improved compared to the 2019 offering of the course. No students in 2021

[12] Kussmaul, C., private communication, 2021.
[13] Katz, J., Introductory Fluid Mechanics, Cambridge University Press, 1st edition.
[14] Phillips, J., “Thermodynamics with ‘POGIL’”, Joint European Thermodynamics Conference, Prague, 2021.
[15] Reynolds, W.C. and P. Colonna, Thermodynamics, Cambridge University Press, 1st edition. 2018.

received a D, F or withdrew from the course during the semester, while 20% of the students in 2019 fell into those categories.

Table 2 – POGIL-related Comments from Student Course Evaluations on the Spring 2021 Thermodynamics Course

Question: What aspects of the course did you find particularly effective?
The POGIL exercise were very helpful. It help me understand the topic and the concept better than just listen to the lecture alone. The POGIL exercise given for each topic is a great idea because it help us to be ready for the future problems that we'll have to tackle.
The POGIL exercises were very effective in giving us students the opportunity to put the skills we just learned to use. I think the amount of POGIL exercises in this course was fine. There were not too few or too many.
I like each POGiL exercises.
The working together in class on poodle [sic] exercises was very effective. It helped understand the discussion for the day.
Pogil exercises were helpful, however they needed more space to work out the problems on the sheet.
POGIL exercises This is a great way to reinforce my idea of what I learned in the lecture and improved teamwork.
Question: What course improvements would you suggest?
Although the POGIL exercise are a great way of learning, sometime it can be a time consuming process and take up too much class time
Near the end of the course, we did a POGIL exercise on specific molar enthalpies that I believe we were not completely prepared for. Giving students more guidance on how to use those equations would improve the course.
More space on the Pogil sheet to perform calculations and such.

<u>Heat Transfer</u>

The author also developed POGIL exercises for a Heat Transfer course (ENGR 422) in the fall 2021 semester. Again, a non-POGIL-based textbook was used, but several of the POGIL activities were developed from examples given in the textbook.[16] This course was also taught entirely face-to-face.

Only four students were enrolled in this course, so it is difficult to draw statistically significant conclusions from the results. Nevertheless, no student earned a grade less than a C, nor did any withdraw from the course during the semester.

<u>Materials Science I</u>

The final course in which POGIL has been used was the fall 2021 offering of Materials Science I (ENGR 207). The course had 22 students, and the classroom had six large tables each with four chairs, which naturally facilitated breakouts into six groups of three or four students. For the first half of the semester, students were allowed to choose the group they worked with, but in the second half the instructor assigned students to different groups to give them the experience of working with different classmates.

Unlike the previous courses, this course used activities which had been created by an accomplished POGIL practitioner, Elliot Douglas, who was also the author of the textbook used in the course. Douglas

[16] Lienhard IV, J.H. and J.H. Lienhard V "A Heat Transfer Textbook", version 5.10, 2020 (available as a free download from ahtt.mit.edu).

has also created lecture slides to accompany related sets of POGIL activities, and importantly, those slides include his recommendations on how much time to allocate for each activity. Some activities were as short as two minutes to as long as 18 minutes. As was the case in the previous version of ENGR 207, the class met once per week for an hour and 45 minutes and started at 8 a.m. on Tuesdays. In a typical session, five to seven different activities would be completed by the students. While the students were working on an activity, the instructor would walk around the classroom checking on progress, answering questions from a group's designated communicator, and giving suggestions when he saw groups were struggling to find the correct answers. When the time for an activity was over, the instructor facilitated the sharing of results from a group with the full class. Often the concepts were reinforced by asking on-line polls via the PollEverywhere.com tool. This proved to be a good way of checking whether all the students were grasping the concepts and allowed the instructor to explain why certain answers were not correct.

Since the Materials Science textbook by Jones and Ashby, that had been used in the previous offering of ENGR 207, followed a different sequence than Douglas's book, the instructor decided to skip over some sections in Douglas's book in order to cover the same topics that had been covered in the 2019 course. This was done to help in comparing the degree of student learning using the 2019 (lecture only) and 2021 (POGIL) teaching methodologies.

In the POGIL-based class, only one of the 22 students got a course grade less than a C, and no students withdrew during the semester. This compares favorably to three out of 14 students falling into the D, F or withdrawal categories in the 2019 course.

Conclusions & Recommendations

The use of POGIL by a novice practitioner in undergraduate Mechanical Engineering courses has proven to be successful in increasing student learning and classroom engagement while also generating positive feedback in student course evaluations. Figure 1 compares the grade distribution in five Engineering courses taught by the author using a traditional lecture-only method to the grade distribution in six similar Engineering classes taught by the author that used POGIL activities. As has been reported by others[17,18], POGIL appears to have decreased the number of students who struggled to gain mastery of the course content while not decreasing the number of students who got high grades.

Compared to previous versions of the same course taught using a traditional lecture-only format, the use of POGIL activities required a reduction in the amount of material that could be covered in one semester by 5 to 10% when using non-POGIL-oriented textbooks and POGIL activities created by the novice practitioner. However, this was not the case when using a textbook specifically written for use in POGIL classes and using activities created by an experienced POGIL instructor with recommended breakout times.

[17] Farrell, J.J., R.S. Moog, and J.N. Spencer, "A guided-inquiry, general chemistry course", Journal of Chemical Education, 76(4), 570-574, 1999.
[18] Simonson, S.R. and S. Shadle, "Implementing process oriented guided inquiry learning (POGIL) in undergraduate biomechanics", Journal of STEM Education: Innovations and Research, 14(1), 56-63, 2013.

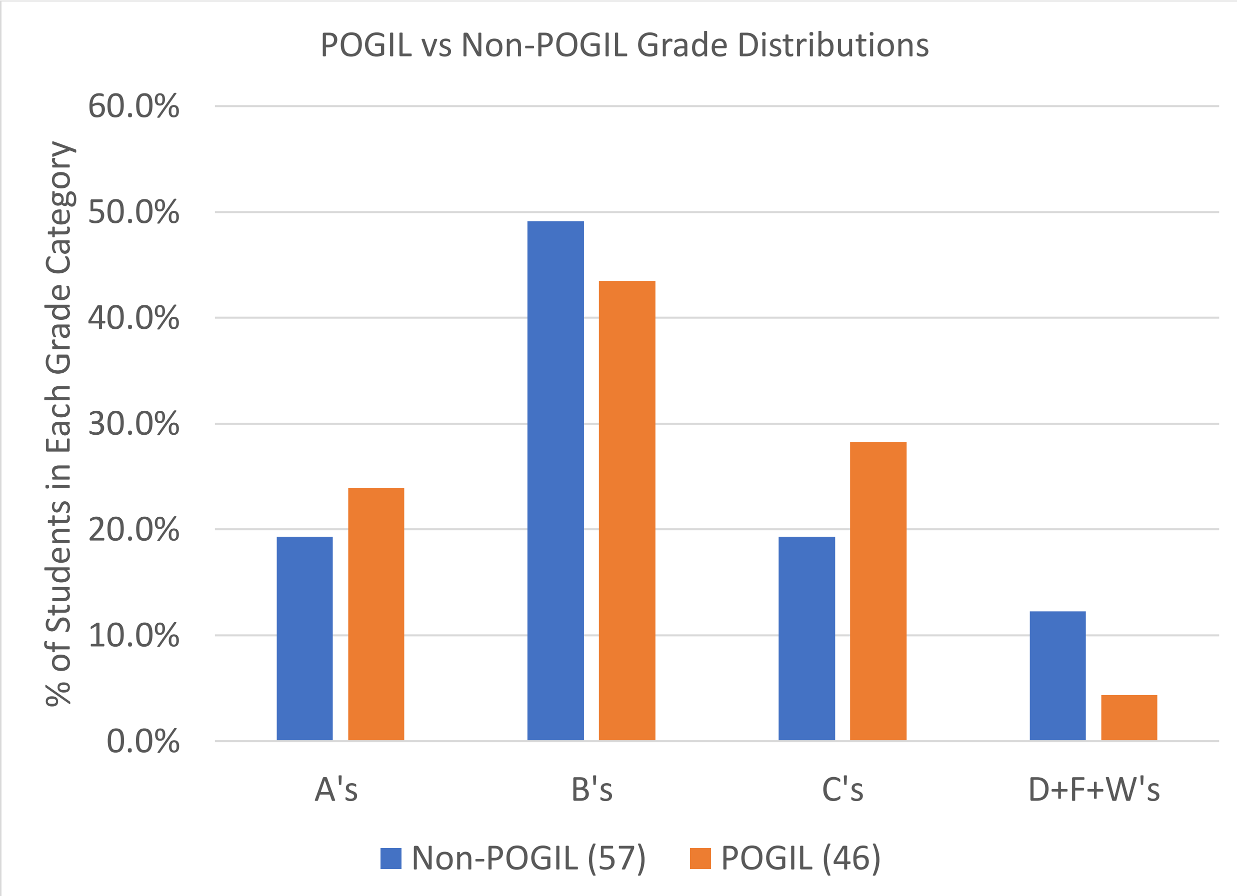


Figure 1 – Grade Distributions of Courses Taught with and without Use of POGIL in the Classroom

For Engineering educators who are interested in including the POGIL methodology in their classes, the following implementation plan is recommended:

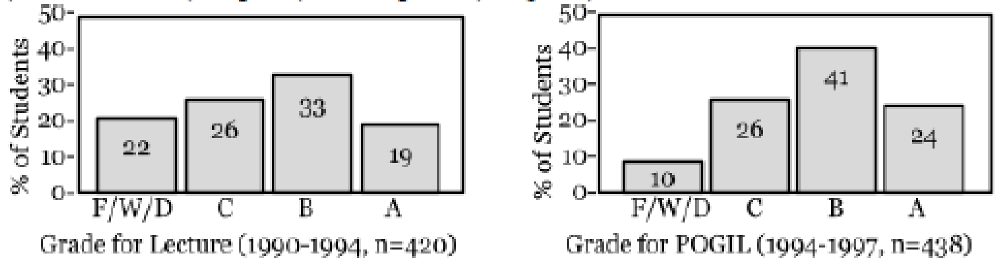
- participate in a Fundamentals of POGIL training seminar offered by the POGIL Project
- start with small steps such as incorporating one activity per lecture
- build from there

Also, use POGIL activities that have already been created for the subject being taught as this will decrease the effort required to implement POGIL. However, it may be necessary to develop your own activities as the POGIL content in Engineering is still limited.

APPENDIX A – EXAMPLE POGIL EXERCISE WRITTEN BY C. KUSSMAUL

Process Oriented Guided Inquiry Learning (POGIL) (1 of 2)

John Farrell, Richard Moog, and James Spencer (*Journal of Chemical Education*, 76(4), 1999) studied how POGIL affects student learning. Roughly 860 students took introductory college chemistry before (420) and after (440) the instructors switched from a traditional **lecture** style of teaching to a **POGIL** style. The bar graphs below shows the final letter grades. *(F=fail, W=withdraw, D=poor, C=acceptable, B=good, A=excellent)*



1. Which style of teaching (lecture or POGIL):		
a.	... had the most B grades?	
b.	... had the most D/W/F grades?	
2. Which category of grades (A, B, C, or D/W.F):		
a.	... **increased** the most from lecture to POGIL?	
b.	... **decreased** the most from lecture to POGIL?	

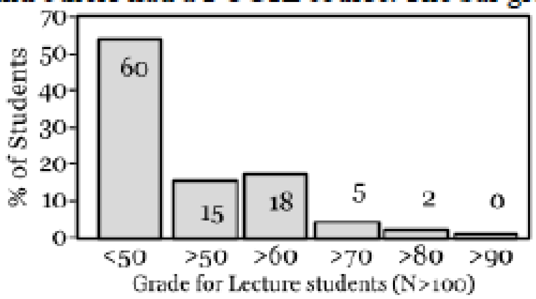
3. Why might researchers combine the grades of D, W, and F for analysis?

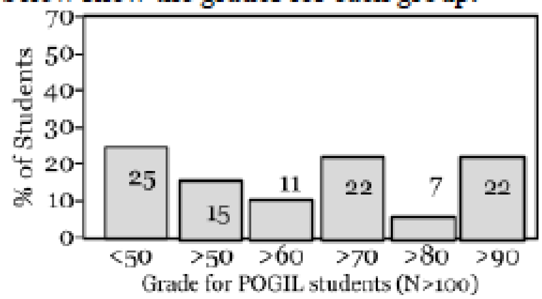
4. What do these results suggest about traditional and POGIL classes?

5. ❔ (optional) What **other factors** might affect the changes from pre to post?

Process Oriented Guided Inquiry Learning (POGIL) (2 of 2)

Suzanne Ruder and Sally Hunnicutt (in Moog & Spencer, eds, *Process-Oriented Guided Inquiry Learning*, 2008) studied how POGIL affects student learning. On the first day of *Organic Chemistry II*, roughly 200 students took an unannounced (surprise) pre-quiz on content from *Organic Chemistry I*, where some students had a **lecture** course, and others had a **POGIL** course. The bar graphs below show the grades for each group.





5. What percentage of students:

a.	... from the **lecture** course scored <50?	
b.	... from the **POGIL** course scored <50?	
c.	... from the **lecture** course passed the quiz (70 or better)?	
d.	... from the **POGIL** course passed the quiz (70 or better)?	

6. What do these results suggest about traditional and POGIL classes?

7. 🔑 POGIL classes tend to spend **more time on fewer concepts**, and some students and teachers worry about the concepts that aren't covered. Explain whether or not these concerns are supported by the data.

8. ❔ (optional) What **other factors** might affect the results in the two courses?

APPENDIX B – EXAMPLE THERMODYNAMICS POGIL ACTIVITY WRITTEN BY J.N. PHILLIPS

ENGR 339 – POGIL Exercise – Entropy Production by Heat Transfer

Purpose: the purpose of this exercise is to show how the 2nd Law of Thermodynamics requires heat to flow from hot to cold systems.

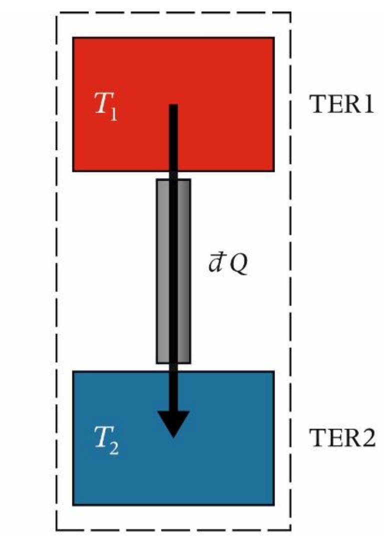
Background: A Thermal Energy Reservoir or TER is an imaginary system that consists of large mass that maintained at constant volume and constant temperature. A TER acts as a "source" or "sink" for energy transfer as heat. The Ohio River serves as a TER for the Xxxxxx coal power plant in nearby Xxxxxxxx.

From the Gibbs equation and an energy balance around a control mass, we have seen that the following holds:

$$dS = \frac{1}{T}\delta Q$$

Where T is the absolute temperature at the boundary of the control mass where the heat transfer occurs.

Critical Thinking Questions: Consider the situation shown in figure (a) below.



(a) The combined system is isolated.

TER1 is at a hotter temperature than TER2. There is a rod conducting heat, δQ, from TER1 to TER2, and everything is at steady state. The combined system of TER1, TER2 and the conducting rod are assumed to be isolated from the surroundings, so no work or heat is transferred across the dashed line.

Answer questions 1 through 4 in 15 minutes:

1. Draw the conducting rod on the whiteboard and show all energy flows in and out as well as the temperatures at the boundaries where heat is transferred.

2. Write an entropy balance for the conducting rod on the whiteboard. Is there any accumulation of entropy in the rod?

3. From your entropy balance, can you show that the incremental production of entropy, $d\mathcal{P}_s$, > 0? Be prepared to defend your answer.

4. Without changing the magnitude of δQ, how could the magnitude of $d\mathcal{P}_s$ be minimized?

Answer the following questions in 5 minutes:

5. Now consider a situation in which heat is flowing from TER2 to TER1, but T_2 is still less than T_1. Write an entropy balance for the conducting rod on the whiteboard.

6. From your entropy balance, can you show that the incremental production of entropy, $d\mathcal{P}_s$, $\geq$0? Be prepared to defend your answer.

7. Is this situation possible?