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Lessons Learned from the Use of Active Learning Strategies in Undergraduate Mechanical Engineering Courses

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Abstract

Active learning strategies, defined by one university's learning center as any type of activity during class that engages learners in deep thought about the subject matter, have been used by the author in a variety of undergraduate Mechanical Engineering courses and have been shown to increase student knowledge. While many of the courses have employed a strategy similar to the Process-Oriented Guided Inquiry Learning (POGIL) pedagogy, other strategies have been used in specific courses. Those strategies include Open Pedagogy assignments in which students develop wiki-pages that are shared with classmates via a learning management system (LMS), student mini-lectures, and design-your-own lab projects.

The POGIL pedagogy was started in the 1990s by a group of Chemistry professors to improve learning in their field but has since spread to other STEM subjects and even non-STEM subjects such as music. However, the availability of materials to facilitate the use of POGIL in Mechanical Engineering courses has so far been limited to Materials Science. This paper describes results from the development and use of more than 120 guided inquiries or worksheets on which students work on in small groups of 3 or 4 to answer a series of questions for Thermodynamics, Fluid Mechanics, Heat Transfer, and Instrumentation courses.

Results from end-of-course grades in six different courses have shown an increase in student knowledge in the classes taught with the POGIL-like strategies compared to the same course taught with a traditional lecture style. The fraction of students receiving D's, F's or W's dropped by half, while the fraction of students receiving A's increased by seven percentage points.

Background

The concept of active learning strategies has been defined by Prince as "any instructional method that engages students in the learning process. In short, active learning requires students to do meaningful learning activities and think about what they are doing" [1]. Additionally, a comment made by Beheshti in a webinar describing best practices for delivering on-line engineering courses during the Covid-19 pandemic succinctly summarizes the reason why active learning strategies are effective: "the one who does the work does the learning" [2].

After working in the energy industry for more than 30 years, in 2018 the author became a full-time faculty member for an undergraduate college engineering program. He started teaching classes the way he was taught in the USA in the 1979-1986 time frame – that is using the "Sage on the Stage" method in which a knowledgeable professor lectures, typically using a chalkboard, to students for the entire class period. Students were expected to take notes during the lecture, review those notes, read the corresponding sections of the textbook, ask questions of the professor when something was not clear, and solve problems in weekly homework assignments.

The only modernization of this strategy was the use of PowerPoint slides instead of a chalkboard; however, a whiteboard was also used for describing concepts when it was deemed appropriate. In short, this was a passive learning strategy.

While the author, having done hundreds of presentations in industry settings, felt confident in his ability to produce effective slides and intentionally drew on his experience to include stories of "real life" applications of what was being taught, colleagues who observed the author teaching noticed that students became unengaged with the lectures after 15 to 20 minutes.

The author also noted that while his end-of-course evaluations from students were overwhelmingly positive, there was still a substantial fraction of students who simply "did not get it" as evidenced by the number of students who received grades of D or F or withdrew during the semester. The author felt certain there must be a better way than the traditional lecture method that could get through to more students and keep students engaged with the material.

Something of an epiphany occurred while talking with a Computer Science colleague about the inability to keep students engaged in class. The colleague asked, "have you heard about POGIL?" "What's POGIL?", was the natural reply.

POGIL stands for Process Oriented Guided Inquiry Learning. The POGIL Project, a non-profit organization dedicated to widening the use of POGIL, describes this pedagogy as "a student-centered, group-learning instructional strategy and philosophy developed through research on how students learn best" [3]. The key element in POGIL is the use of worksheets, or "guided inquiries" that students work together to answer in small groups of three or four during a class session while being guided by the instructor. The inquiries are meant to mimic the natural learning process of exploration, discovery, and application [4].

The POGIL Project has fostered the development of textbooks which include guided inquiries that have been tested in classrooms. However, only one of those textbooks is targeted for a Mechanical Engineering course [5], but fortuitously for the author, it was in subject he taught: Materials Science. He began using guided inquiries from the textbook during the winter 2020 semester and saw immediate improvement in student engagement.

In 2022, the author published a paper describing his initial efforts of creating POGIL-like guided inquiries for other subjects they taught: Fluid Mechanics, Thermodynamics, Heat Transfer and Instrumentation & Statistics [6].

POGIL-Like Activities

The term "POGIL-like" is used here as the guided inquiries developed by the author have not been reviewed and approved by the POGIL Project as official activities. Nevertheless, after attending an introductory workshop offered by the POGIL Project and participating in a two-year-long cohort learning group of professors using the POGIL methodology with an experienced POGIL practitioner as the facilitator, the author believes he has implemented the methodology to something beyond a novice level.

As described in the 2022 paper [6], a major part of the effort to incorporate POGIL-like activities into Mechanical Engineering courses was the development of guided inquiries that the small teams of students would use during classes. In total more than 120 guided inquiries have been created and used in the classroom. Most have gone through a second iteration based on feedback received directly from students and from the author's own observations of what caused students to struggle to find answers to some questions. An example of a guided inquiry created by the author for a Thermodynamics class is provided in Appendix A and the full collection of guided inquires written by the author can be found on a publicly accessible shared drive [7].

As part of the POGIL Project's cohort tutoring sessions, the author received guidance that activities which are computationally intensive tend to bog down a student team. This is due to the roles that are assigned to each team member, which is part of the "process-oriented" aspect of POGIL. In a team of four students, one is assigned to be the manager or coordinator, one is assigned to the communicator (the only one who may speak to the instructor or other teams), one is assigned to be the researcher (the only member of the team who may use a computer or calculator) and one is assigned to the role which the author has named "train conductor" because they have to make sure everyone is "on board" (agrees with the answer) and "pays the fare" (contributes to the discussion). If a question is computationally intensive, three of the four members could be sitting around for several minutes while the researcher completes the calculations.

Based on this guidance, the author has modified some guided inquiries to deemphasize calculations or has changed the instructions to have all students work in pairs to perform calculations (one student "drives" the computer while the other serves as a quality check).

The results on student learning of switching to an active learning strategy in six different courses taught by the author are summarized in Figure 1. The percentage of students who received a D, F or W from those classes taught using POGIL and POGIL-like activities declined to 5% compared to 12% in the same courses taught by the author using a traditional lecture-only method. At the same time the percentage of students who received an A increased from 19 to 26%. This result matched the experience of others who have observed that POGIL helps students who have typically struggled to master content while not decreasing the number of students who achieve high grades [8], [9]. In summary, through the use of POGIL-like activities about half the students who previously might have received a D or an F were getting C's, and about 10% of the students who would have previously been expected to get a B were getting A's.

It should be noted that not all classes saw this exact trend. Figure 2 shows the grade distribution from three sessions of a Material Science I course taught by the author. The first session, in Fall 2019, used traditional lectures, while the next two sessions used POGIL activities from [5]. As seen in the figure, the first time POGIL was used, the fraction of students who received Ds, Fs or Ws did decline, but so did the fraction who received As. The second time POGIL was used, no students received a D, F, or W, and the fraction of students that received A's rose back to what was seen with a traditional lecture pedagogy. This is likely an indication of the author's improvement at facilitating classes which use POGIL pedagogy. Interestingly, the percentage of students getting either an A or a B in the POGIL classes was 78% in fall 2021 and 77% in the fall

2023 class compared to 43% when lectures were used. This indicates that even when implemented by a novice practitioner, POGIL can benefit a significant fraction of students.

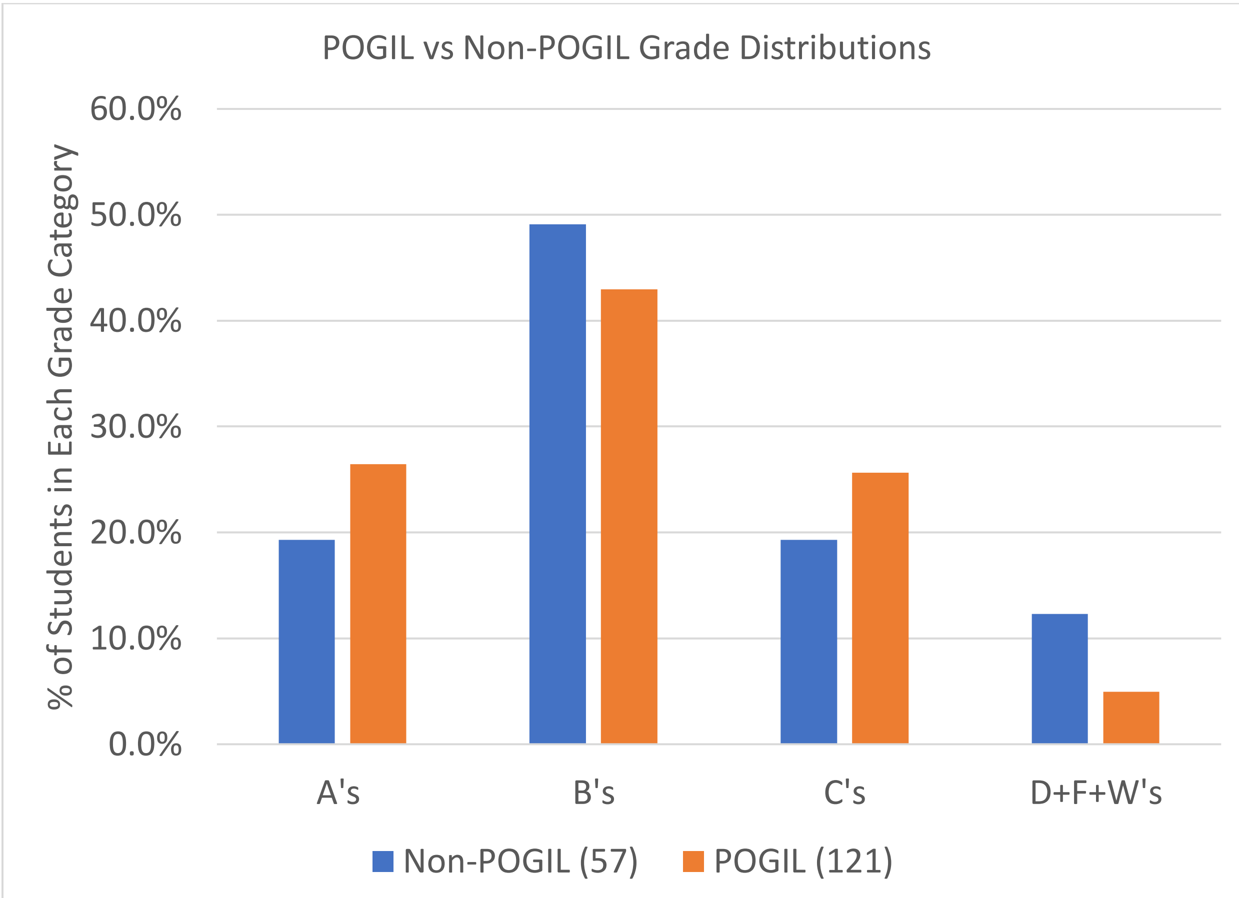

Figure 1 – Comparison of Grade Distributions from Same Courses Taught by Author Using Traditional Lectures versus Using POGIL-like Activities.

The positive end of course feedback from students on the use of POGIL-like activities that was reported in [6] has continued in the two years since that publication was issued. Among the student feedback that mentioned "POGIL", "guided inquiries", or "group exercises" during the 2022-23 and 2023-24 academic years, 80% of the comments were positive.

A curious trend in the feedback was that several students recommended using a different textbook in the Material Science courses. This was the only textbook used by the author that was specifically written to incorporate POGIL exercises. While the students stated they did benefit from the exercises, they felt the textbook did not go into enough detail on several topics.   One student wrote that they felt the textbook was "just a rough guide instead of [providing] a firm basis for the class". No negative comments were raised about the textbooks used in the author's other courses. Those textbooks were more traditional in structure, so apparently the students prefer guided inquiries in class to help them understand new concepts but also want textbooks that explain those concepts in detail.

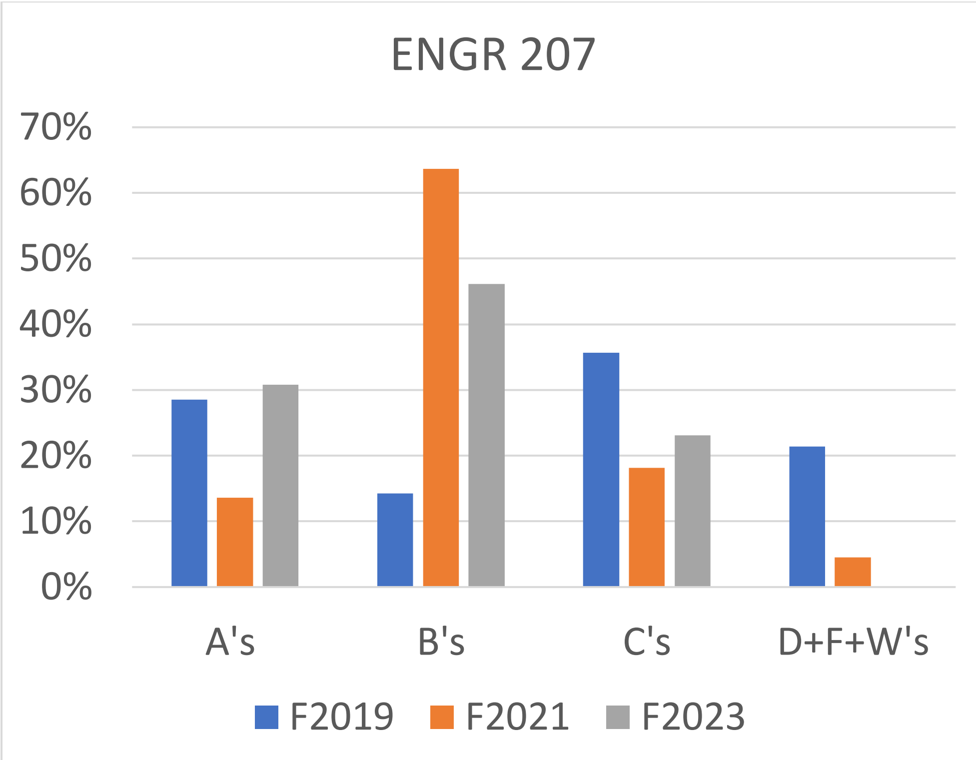

Figure 2- Grade Distributions from Three Sessions of a Materials Science I Course. Fall 2019 Used Traditional Lecture Format, While Fall 2021 and 2023 Used POGIL Format.

Open Pedagogy & Renewable Assignments

As part of the response to the Covid-19 pandemic, the author's institution provided training to all instructors on how to design effective on-line courses. It was during one of those sessions that the author was exposed to the concepts of "open pedagogy" and "renewable assignments".

According to Wiley in [10], open pedagogy involves the use of assignments which are "impossible without the permissions granted by open licenses" granted in open education resources (OER). Wilson goes on to state that an open pedagogy assignment "leverages the reuse, revise, remix, redistribute permissions of [OER] in order to enable students to extend and improve the official instructional materials required for the course". Additionally, [11] describes open pedagogy as "the practice of engaging with students as creators of information rather than simply consumers of it".

Renewable assignments are an example of open pedagogy. As explained by Wiley and Hilton [12] they differ from traditional "disposable assignments" by having a student create an "artifact" which is then made public and openly licensed. Renewable assignments are thought to better motivate students since they involve the creation of something lasting which others will see rather than something that is thrown away once a course is over.

Wiki-Page

One example of a renewable assignment given in the training the author received was having students create a “wiki-page” on a course’s subject and having future students build on what previously students created. According to [13], a wiki is “is a form of online hypertext publication that is collaboratively edited and managed by its own audience directly through a web browser.”

For a Manufacturing and Design course, the author chose a textbook [14] which covers 12 of the more commonly used manufacturing process in detail and then has one chapter titled "None of the Above” which gives a quick introduction to 12 additional processes. To expose the students to more information on these less common processes, and to give the students practice in researching a manufacturing process which was new to them, the author created an assignment which called for each student to create a wiki page on one of the processes covered in the None of the Above chapter.

The author’s institution uses Moodle [15] as its learning management system. Moodle includes a wiki as one of the assignment templates which an instructor can use. Prior to introducing the assignment, the author created a top-level wiki page that simply contained the names of the various processes covered in the None of the Above chapter. Students could then create wiki pages that linked to the corresponding name in the top level page. After spending no more than 10 minutes in class demonstrating to students how to use the wiki editor in Moodle, all students were able to create a page. Figure 3 shows a screenshot of the Moodle wiki assignment page with instructions on what students should include in their wiki page.

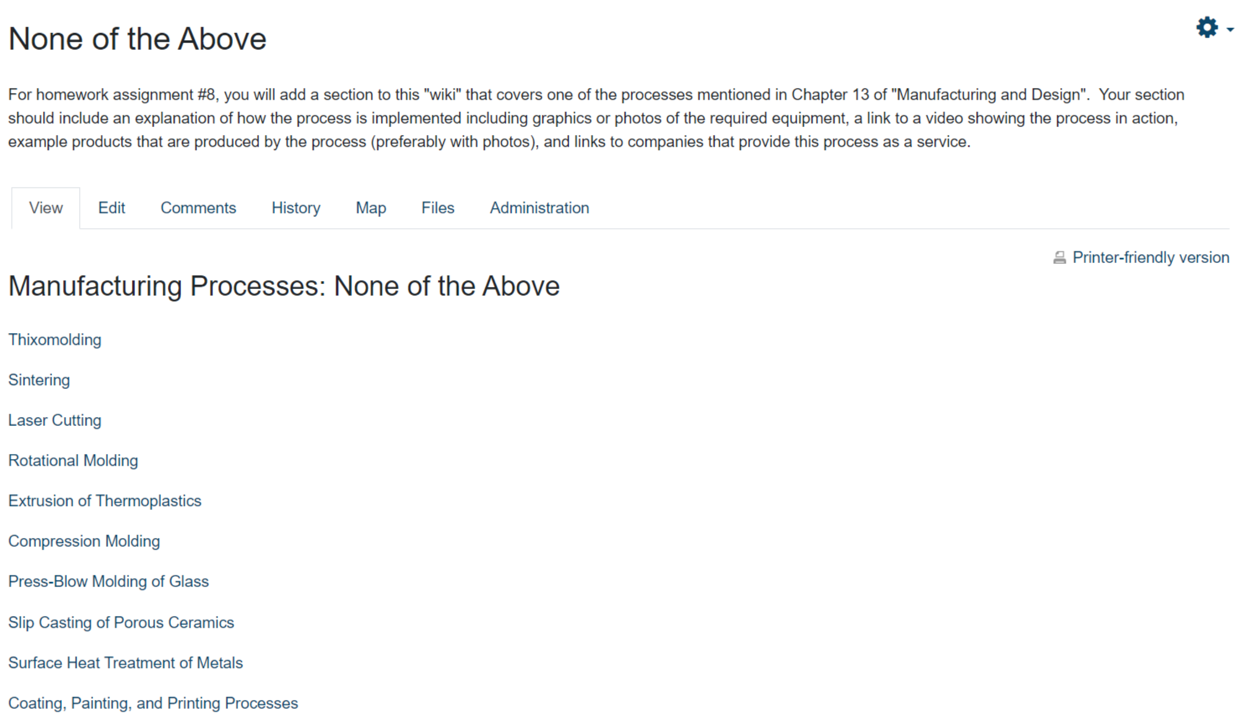

Figure 3 – Screenshot from Learning Management System Showing Wiki Homework Assignment

To encourage students to avoid procrastination and to give them a sense of control in the assignment, the instructor told the students they could claim any process they were interested in researching by starting a new page that had the name of the process as the title and link it to the top-level page. If more than one student expressed a desire to work on the same process, the instructor would agree to allow them to work together by splitting the process into different sub-topics. For example, under the title of "Coating, Painting and Printing" might be spilt by assigning paints and coatings to one student and printing to another.

The students were given a deadline for completing their page and were told they would be graded based on the page containing the follow content:

- an explanation of how the process is implemented (30 pts max)
- graphics or photos of the required equipment (20 pts max)
- a link to a video showing the process in action (15 pts max)
- example products that are produced by the process (15 pts max)
- photos of products (5 pts max)
- links to companies that provide this process as a service. (15 pts max)

On the day the assignment was due, the class consisted of each student taking turns showing their page's content to the rest of the class and describing what they had learned about in the process. All students also had access to their classmates' pages via Moodle. As a result, all students were exposed to more information on multiple manufacturing processes than was contained in their textbook, and each student had become the class expert on one of those processes. This was a clear case of "the one who does the work does the learning", but the others also gained some knowledge. Out of the ten homework assignments in the course, the average grade on the wiki page assignment was the second highest, which also indicates good student engagement with the task.

<u>Design Your Own Lab</u>

Another example of open pedagogy was allowing students to select a topic that they wished to investigate in more detail for a lab assignment. The author has used a "design your own lab" assignment in both an Instrumentation & Statistics class and a Heat Transfer course. Both courses included lab sessions throughout the semester, and all but the final lab were based on activities developed by the instructor and provided to the students in written guidelines.

The final lab assignment in both courses required the student to decide what they wanted to investigate. For the Instrumentation course, the instructor took inspiration from MIT's "Go Forth and Measure" lab [16]. The author told students they could measure anything they were interested in and could use any of the instruments which had been covered in the course. They could also use instruments which they had used in previous courses, and they did not need to limit themselves in taking measurements in the laboratory – they could take measurements anywhere on campus. Students were also told that while they could assist each other in their experiments, each student had to design their own experiment and had to write a report documenting that experiment.

In the Heat Transfer course, the students were told they could use any of the lab equipment that they had used in earlier labs provided they used the equipment to investigate something that had not been examined in the previous labs. For example, they could use the department's heat exchanger testing apparatus to investigate the performance of plate and fin exchanger since the previous lab had only compared a shell and tube exchanger in counterflow and parallel flow configurations. As the Heat Transfer course is the culmination of a three-course Thermal Sciences sequence, students were also allowed to use equipment from labs conducted in their Thermodynamics and Fluid Dynamics courses. Since the department only had one copy of most of the equipment used in its Thermal Science labs the Heat Transfer students were allowed to work together on designing, conducting, and documenting their experiments.

In addition to getting the students more engaged in the lab activity, this assignment also helped students achieve the ABET Student Outcome #6 which calls for students to acquire an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions [17]. While the previous lab assignments in both courses helped the students achieve most of this, only the final assignment helped them show they could develop experimentation.

The design your own lab assignments were well-received by the students. The Instrumentation and Statistics lab resulted in a wide variety of experiments being conducted. Student athletes tended to measure something related to their sport or fitness training. For example, one student attached an accelerometer to the barbell they used for weight training and measured how well they were able to maintain a consistent velocity while lifting a weight through ten repetitions. Another student, a non-athlete who did not like the cold temperatures in their dorm room, used a thermal imaging camera to identify the spots where cold air was leaking into the room, and this information was passed on to the college's facilities department for possible mitigation.

Also for the Heat Transfer design your own lab, the students were required to use the template for technical papers submitted to ASME conferences. This would help students achieve ABET Student Outcome #3 which calls for students to demonstrate "an ability to communicate effectively with a range of audiences" [17]. By showing that they were able to write a professional quality technical paper, students would partially attain Student Outcome #3. However, the initial time this assignment was given, the author was disappointed in the quality of the technical papers. With a few exceptions, they were very thin on details.

Consequently, the second time this assignment was used in the Heat Transfer course, the author developed a detailed grading rubric (see Appendix B) which was modelled on rubric created by Whitty [18]. To mimic the actual process of submitting a paper to an ASME conference, the students were first required to submit a draft of their paper, which the author graded using the rubric and returned to the students. However, instead of giving the students a grade based on the rubric, they were awarded 20 points toward the final paper grade if the draft was submitted on time, and 16 points if it was submitted later. The reason for providing the grade based on the rubric was to motivate the students to do better on the final version which would have an 80% weight on the assignment's grade.

This two-stage approach coupled with the detailed rubric was highly successful in getting the students to write a more professional quality technical report. The length of the reports increased from an average of three pages in fall 2019 to six pages in fall 2021, and one student from the 2021 class had a revised version of their paper accepted for presentation at a regional ASEE conference [19].

Real-life Problem Definition in Introductory Engineering Design Course

In [20], a textbook on the engineering design process, the authors recommend as a first step in any design project to "revise the problem statement" that was initially given to the design team by a client. The revised statement should include the objectives and constraints of the client and the important functions they want the design to be able to perform. In addition, the statement should be free from "errors, biases, and implied solutions." As part of the process of revising a problem statement, it is important to ask probing questions of the client that reveal what they truly need. For example, if the client says, "I need a drill", the design team should say "it sounds like you need a hole, and you assume a drill is the best way to create one. Is that right?"

Rather than simply lecture to the students about how to communicate with a client for the purposes of revising a problem statement, the author has created an active learning assignment to help the students practice the techniques described in [20]. A field trip is made to a collection center of the regional recycling district, and the director of the district describes to the students the biggest challenges the recycling industry is facing and asks them to develop ideas which could help address those challenges. The students then have time to ask questions of the director to better understand what is needed.

Once they return to campus, students are assigned to small teams and each team must pick a design challenge to work on. The teams have two weeks to prepare for a presentation to the recycling district's director. In addition to focusing on the students' presentation skills, the grading rubric for the assignment is highly weighted on how well the students show a clear understanding of the problem and the challenges to solving it. Only 10% of the grade is based on the quality of the preliminary ideas the students develop for addressing the challenge because the main purpose of this exercise is to improve information gathering skills rather than to show innovative thinking.

Feedback from the students has shown that they do not view it as a "disposable assignment". Often they have remarked on how it seems like a "real" job assignment for an engineer, and while the recycling district has not directly implemented any of the ideas proposed by the students in this assignment, it has influenced their thinking on how to solve the problem [21]. Consequently, the students view the assignment as having created something of lasting value.

Student Feedback

All students at Hanover College are asked to give anonymous feedback via an on-line survey at the end of each course. The questions in the survey have remained the same during the period the author has been teaching at the college, so it is felt the responses provide a reasonably consistent method of judging student satisfaction with the author's courses taught with passive learning strategies compared to those taught with more active learning strategies. Two questions from the survey have been used as surrogates for course effectiveness and student satisfaction with a course:

- Question 1: As a result of this course, my interest in the subject has ____. (Response options are: strongly decreased, decreased, remained the same, increased, strongly increased)
- Question 2: Overall, I rate this an excellent course. (Response options are: strongly disagree, disagree, neither agree nor disagree, agree, strongly agree)

For question 1, the percentage of students responding "increased" or "strongly increased" was used as an indicator of effectiveness of the course, and for question 2 the percentage of students responding "strongly agree" was deemed to be a good indicator of student satisfaction.

Table 1 summarizes the data from the two questions. The use of active learning strategies in the Instrumentation & Statistics and Heat Transfer courses was coupled with 36 percentage point improvements in the proportion of students who reported the course increased their interest in the topic. It is noted that both these courses used POGIL-like guided inquiries created by the author and a design your own lab assignment while also using traditional (non-POGIL) textbooks. In two other courses, Fluid Dynamics and Thermodynamics, which both used the author's guided inquiries but no other active learning strategies, the change in increased student interest was less than +/- 5%, which is within the normal fluctuation one would expect from these surveys. In the two Materials Science courses, which used POGIL guided inquiries with a POGIL-specific textbook, the percentage of students who reported an increased interest declined by 20 and 45 percent. This is even though overall student grades increased when POGIL was used. Some of this may be due to dissatisfaction with the textbook mentioned previously and some may be due to these being the first courses in which students have encountered a full POGIL pedagogy.

Interestingly, the percentage of students who agreed that the course was "excellent" dropped by 17 percentage points for the first Materials Science course but increased by nine percentage points in the second course. This may be due to an increased comfort level with the POGIL technique in the second course.

The percentage of students strongly agreeing that the Instrumentation & Statistics, Heat Transfer, Fluid Dynamics and Thermodynamics courses were excellent increased anywhere from 12.5 to 52 percentage points, which suggests that the combination of guided inquiries written by the instructor and a traditional textbook meaningfully increased student satisfaction with these courses that are often dreaded by many other engineering students.

Table 1 – Summary of Student End-of-Course Feedback

	Passive Learning Applied		Active Learning Applied		
Course	% Increased Interest	% Strongly Agree Excellent Course	% Increased Interest	% Strongly Agree Excellent Course	Comments
Introduction to Engineering Design	68.2	41.5	N/A	N/A	Real-Life Problem, Traditional Lectures
Materials Science I	72.7	45.5	52.4	28.6	Guided Inquires & POGIL Textbook
Materials Science II	100	40.0	54.5	63.6	Guided Inquires & POGIL Textbook
Instrumentation & Statistics	41.6	50.0	77.8	62.5	Guided Inquiries, Design Your Own Lab
Fluid Dynamics	75.0	25.0	71.4	62.5	Guided Inquiries, Traditional Textbook
Thermodynamics	50.0	16.7	54.3	57.1	Guided Inquiries, Traditional Textbook
Manufacturing & Design	N/A	N/A	95.9	75.0	Wiki Page, Plant Tours, Traditional Textbook
Heat Transfer	50.0	33.3	85.7	85.7	Guided Inquiries, Design Your Own Lab

Two other courses in Table 1 did not undergo a change in teaching strategy but were included as they provide some additional insights. The first, an Introduction to Engineering Design course targeted for first-year students uses a traditional lecture format but does include the "real life problem definition" assignment described previously. While the increased level of interest in the topic is comparable to or higher than most of the courses which used active learning strategies, less than half the students strongly agreed that it was an excellent course. Written comments in the end-of-course surveys indicate that students do not like sitting through long lectures and would prefer more hands-on projects.

The second course, which did not undergo a change in strategy, was a course on Manufacturing & Design. In addition to having the Wiki page assignment, the course textbook [14] has discussion prompts embedded in the chapters that have been used by the author as the basis for guided inquiries but without formal role playing. Also, instead of lab sessions, the class makes visits to local manufacturing facilities to see the processes in action that were discussed in class. Students then write two-page trip reports that allow students to focus on what interested them the most from the visits. These strategies appear to have been highly effective in generating student interest in manufacturing and have resulted in 7% of the students strongly agreeing that it is an excellent course.

Conclusions

Today's undergraduate engineering students do not respond well to the teaching techniques employed by engineering faculty 40 years ago. Instead, having grown up in a world connected by smart phones to the vast array of information on the internet, they want to have control of the way they receive information. Accordingly, active learning strategies put students at the center of the learning process. In doing so, they become more engaged in the classroom and increase their uptake of knowledge.

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Appendix A – Example of a Guided Inquiry Worksheet for Thermodynamics Course

ENGR 339 - Guided Inquiry – Excess Air Combustion

Purpose: the purpose of this exercise is to examine the impact of using excess air in a combustion reaction.

Background: Most devices that burn fuel are operated with excess air, which means there is more air present in the reactants than is needed for stoichiometric combustion. The reason for this is that the consequences of operating with a deficiency of air (i.e., fuel-rich) are not good: unburned hydrocarbons, soot, and CO will be part of the products of the reaction. Since exact control of the flows of fuel and air are difficult to achieve, it is better to operate with excess air so that any fluctuations in flows will not result in a fuel-rich condition.

Critical Thinking Questions:

Work together to answer the following questions in 8 minutes:

1. If a combustion process is operated with excess air, what will happen to the excess O_2 that is supplied to the reaction?

2. The first half of the chemical reaction for combustion of methane with 25% excess air can be written as: $CH_4 + 1.25 \times 2(O_2 + 3.76N_2) \rightarrow$, write the full chemical equation on the whiteboard for this situation.

Work together to answer the following questions in 10 minutes:

3. What are the mole fractions of all the products of methane combustion with 25% excess air?

4. To what temperature could the exhaust from methane combustion with 25% excess air be cooled down before moisture begins to condense (assume exhaust is at atmospheric pressure)?

Appendix B - Grading Rubric for Design Your Own Heat Transfer Lab Technical Report

Title Page	
1. All elements of required text in place	3 points
2. Abstract accurately summarizes report	3 points
3. Nomenclature includes all parameters used in formulas and text	3 points
Introduction	
4. Introduces the topic	2.5 points
5. Explains what you are investigating/testing and why	2.5 points
6. Describes the theory or technical basis for the experiment	2.5 points
7. Includes appropriate equations	2.5 points
8. All equations numbered properly following ASME format	2.5 points
Materials & Methods	
9. Describes apparatus and instrumentation used in detail	4 points
10. Includes a schematic drawing and/or photos of set-up	2.5 points
11. Describes procedure that was used including test settings	4 points
Results & Discussion	
12. Includes summary of results	2.5 points
13. Includes table(s) and/or chart(s) of key results	4 points
14. Interprets the results	4 points
15. Includes discussion of sources and magnitude of uncertainty	2.5 points
Conclusion	
16. Describes one or two key findings from your experiment	2.5 points
17. Recommends future work that would provide value	2.5 points
End Material	
18. Acknowledgments (who helped you?)	1 point
19. Includes appropriate references (at least four)	4 points
General Appearance and Readability	
20. Adheres to ASME format throughout (including captions)	10 points
21. Quality of figures/photos/graphs	6.5 points
22. Grammar, spelling, punctuation	13 points
23. All acronyms defined, but only the first time they are used	2.5 points
24. Clarity of text	13 points
Total	100 points