AC 2011-731: LEARNING IN LABORATORY COMPLIMENTS TO LECTURE COURSES VIA STUDENT DESIGNED AND IMPLEMENTED EXPERIMENTS

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Abstract

One of the primary goals in engineering education is to equip students with the ability to *apply* knowledge (e.g. principles of science and math from core engineering courses) to complex problem solving situations. Thus, at the culmination of a program of study geared toward building a student's knowledge base, two questions that linger in the educators mind are:

- have students acquired process skills – do they understand how to employ their knowledge in practice?
- have they acquired epistemological skills – do they understand the correct application and limitations of their knowledge and are they able to acquire new knowledge as needed to solve the problem at hand?

These questions have been raised by different generations. In his treatise on *Ethics*, Aristotle concluded "activity in a certain thing gives a man that character … dispositions are attained through actually doing things (250 BC)[1]." In other words, students gain such skills through the practice of *doing things*. The authors investigated how unstructured "open" exercises (a unique approach to learning using unstructured, multidisciplinary assignments) helped students cement their knowledge of concepts in Thermodynamics, Fluid Mechanics, and Heat Transfer. A Thermo-fluids laboratory course required for Senior and Junior Aerospace and Mechanical Engineering students was selected for this study. Students were asked to provide their views of the rigor of the course and its impact on their learning experience. Results indicate they perceived to have a superior grasp of concepts after designing and implementing their own experiments.

Introduction

The ultimate objective of any academic program is for students to gain the ability to transfer classroom learning to practice, for which they will be required to construct and apply knowledge towards problem solving. For example, the consensus outcome for engineering graduates is the ability to *apply* principles of engineering, science, and math to design and analyze real systems or processes[2] . Much debate however exists on the best learning practices to build these skills. Proponents of problem-based learning (or project-based learning) argue that the bulk of acquired knowledge, skills, and dispositions are cultivated by the student[3,4]. However, if the student experience is deemed this important to his or her future, the question remains: what is the educator's role in helping students pull information together for assimilation and application? Should the student be subjected to rote learning or should they be given an opportunity to exercise their acquired knowledge, skills, and dispositions within constraints?

As the focus of this paper is the undergraduate junior/senior engineering student, the National Research Council (NRC) suggested an approach to learning which seemed applicable to this group. NRC observed that all new learning involves transfer based on previous learning[5].

Transfer is a degree of understanding beyond memorization; it indicates the ability to process information and integrate knowledge in new contexts. Three influences for successful transfer include (a) the degree of mastery of the original matter, (b) transfer, and (c) time to learn. Without an adequate level of initial learning, transfer cannot take place. It was also observed that the time to learn is proportional to the amount of material being learned. Bandura observed similar developmental stages in his social learning theory[6]. He suggested three stages that progresses from the preparatory stage, through play stage, to the game stage. At the preparatory stage, a meaningless imitation is experienced. At the play stage, role play occurs without unified concept. At the game stage, the individual acts with certain amount of consistency in a variety of situations.

Degree of mastery of the original matter

Engineering programs are known for their rigor. Students at the junior and senior levels have built a significant knowledge base from which to draw on. Typically, they will have taken required courses in math, science and engineering and have received considerable practice in solving well-defined problems. The types of structured problems found in textbooks are designed to ensure students have a grasp of fundamental concepts, but rarely require transfer or generalization to a broader context. Understanding beyond rote memorization is necessary for long term retention and application of new knowledge and skills. On the other hand, mastery of the basics is a prerequisite to transfer and application. While project-based learning activities are often introduced in lower-level design courses, students would not yet have the foundational knowledge to transfer to complex, multidisciplinary problems.

Transfer

With knowledge of the basic principles of engineering, junior and senior undergraduates are prepared to embark on solving ill-defined or unstructured problems. This requires a stronger and more diverse skill set when compared to solving well-defined problems. As a student's habits of the mind develop into professional dispositions, they need substantial practice in this arena. To this end, virtually all engineering programs offer a significant capstone design experience. But is this enough? Many other upper level engineering courses build upon prerequisite knowledge and may also provide opportunities for transfer and complex problem solving. In particular, laboratory courses are excellent candidates as transference or the assimilation of concepts into practice is the ultimate goal. To be effective, however, laboratory instruction must deviate from traditional exercises involving a structured/dictated ("canned") procedure requiring minimal critical thinking by the student.

Time to learn

Solving engineering problems requires drawing from various sources of knowledge and skills. The amount of material to be learned dictates the amount of time to be spent acquiring these skills. NRC observed that learners who find it difficult to understand ideas initially may need more time to explore underlying concepts in order to generate a connection to other information they possess[4]. Attempts to cover too many topics too quickly may hinder learning and subsequent transfer because students (a) learn only isolated sets of facts that are not organized and connected or (b) are introduced to organizing principles that they cannot grasp because they lack enough specific knowledge to make them meaningful.

Junior and senior students have undertaken many courses and complimentary traditional laboratory experiences that offer “canned” or fixed experiments with fixed set of procedures. The authors investigate how students would learn and what impact would result when given an “open” or unstructured type laboratory which requires much more independent thinking and transference on the part of the student.

Method

Class Overview: The unstructured, open laboratory concept was implemented for an upper-level, required Thermo-Fluids course. Two groups of students, those taking the course in summer 2008 and summer 2009, participated in the study. The class met weekly for one and half hours throughout the semester for a one hour credit. Class size was limited to eight students to enable ample guidance from the instructor. At the beginning, students were informed of the format of the course: that they would work together in teams to design, specify, configure, and implement two experiments which would serve to illustrate concepts in thermodynamics, fluid mechanics, and/or heat transfer. The desired outcomes for the course were that students would establish *mastery* of the underlying theory behind their experiments and make connections needed to *transfer* this knowledge to their own designed experiment given an unstructured, open-ended problem statement. In addition, the process would reinforce principles for experiment design, and students would be required to seek new knowledge about the instrumentation associated with thermo-fluids measurements. The course objectives were outlined as:

- Reinforce fundamental principles in Thermodynamics, Fluid Mechanics, and Heat Transfer
- Provide additional design of experiments experience
- Draw a stronger connection in students’ minds of the linkage between the problem and the design of an experiment needed to interpret the problem.
- Provide further opportunity and growth of technical communication.
- Provide an opportunity for creativity and imagination

Review of Prerequisite Material: In order to establish a baseline of knowledge for all students, sixty minutes of each of the first three weeks of the term was dedicated to reviewing fundamentals of thermodynamics, fluid mechanics, and heat transfer with each of the three segments assigned specific week. During this same time period, students also formed teams of three or four and decided on the scope of their two experiments. One experiment was to cover subject matter in thermodynamics/fluid mechanics while the second would cover the heat transfer. The authors felt students needed additional time to learn and process concepts from the prerequisite courses. In addition to providing background material, real world application of theory was discussed to provide students with ideas on potential experiments. An example of review information in heat transfer included discussion and applications of conduction, convection, and radiation, as outlined below:

Conduction

$q_x'' = k\frac{\Delta T}{L}$ Heat flux = rate of heat transfer per unit area

The heat rate by conduction, q_x (W), through a plane wall of area A is then the product of the flux and the area, $q_x = q_x''.A$

Convection

$q'' = h(T_s - T_\infty)$ where q'', the convective heat flux (W/m^2), is proportional to the difference between the surface and fluid temperatures, T_s and T_∞, respectively; and h is the convection heat transfer coefficient

Radiation

$q'' = \varepsilon\sigma(T_s^4 - T_{sur}^4)$ net rate of radiation heat exchange between the surface and its surroundings per unit area of the surface (gray surface)

$q_{rad} = h_r A(T_s - T_{sur})$ net radiation heat exchange, where A is the surface area and

$h_r \equiv \varepsilon\sigma(T_s + T_{sur})(T_s^2 + T_{sur}^2)$

Again, the review of fundamentals was intended to bring students up to speed in what they knew from previous courses. By their junior year, students would have successfully completed applied differential equations, general physics series, and computational methods. The application portion of the class presentation was intended to give students ideas of where such engineering concepts could be used to meet needs of a give problem.

Experimental Designs: In order for the students to have a significant investment in their learning experience, students were given an open-ended problem statement. Simply, they were to design two experiments meeting the following requirements:

- They must have a theoretical basis for which the experiment should be designed to illumine (one experiment must highlight a theory from thermodynamics and/or fluid mechanics, the second must illustrate a concept in heat transfer);
- They must use inexpensive sensors which must be powered (if necessary) and sensed using Measurements Computing Minilab DAQ boards capable of communication with laptops via laptop USB ports;
- They must use standard off the shelf parts or minimal manufacturing;
- They must be compact, with all components ideally fitting in a 12” x 4” x 4” volume (minus the DAQ board);
- They must permit “variation”, e.g., they must permit experimenters to see sensitivity of the results to changes in the experimental parameters;
- They must ideally provide experimenters with choices to optimize results;
- They should reinforce ideas of efficiency and energy loss (and maybe even cost);

- Minus the DAQ board, expenses for a single experiment should be less than $50 (however, great ideas may merit greater expense)

Students had a total of twelve weeks to develop the experiments and test them. The first six weeks were dedicated for experiment one which they were to present at the end of that week. The last six weeks were for the second experiment which was presented in the 12th week. Presentations were both in power point format and actual demonstration of the artifacts.

Experiment Reports: Students were required to document their experimental process with a written report. They were also to give an oral presentation, demonstrating their experiment and results. They were provided the following outline:

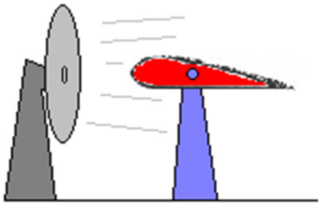
- Theory: Describe the theory upon which the experiment is based.
- Goals: Discuss the goals of the experiment.
- Experiment: Describe the experiment. Include a detailed schematic. All figures should be referred to in detail. Reference should be made both to the physical system and the sensors used to interrogate.
- Experimental Procedure: Detail the experimental procedure used.
- Results: Present the experimental results. Be sure to describe results completely in text. Refer to the graphical and/or tabular results.
- Discussion: Discuss the significance of the results.

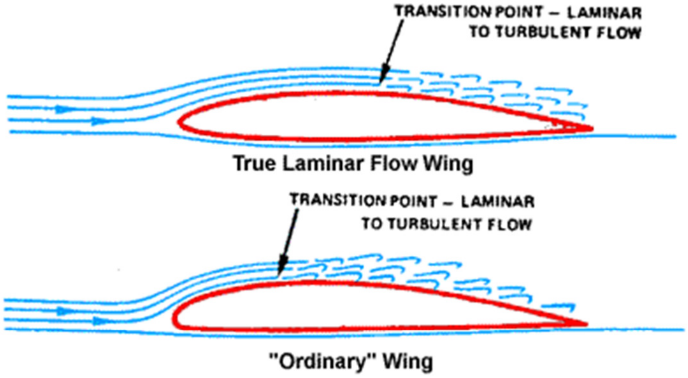
Student Experiments

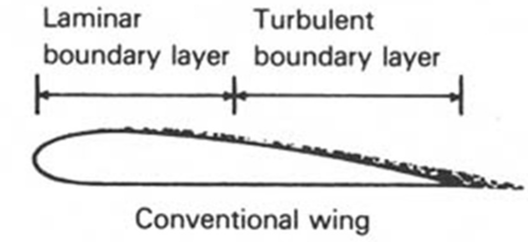
In self-formed teams of four students per group, students identified, discussed, and selected one of their proposed topics for developing and experimentation. A total of four proposals were made by each team with one proposal per team member. Each team developed its criteria for the basis of final topic selection. Teams used the given *experiment report* section as their checklist for guiding their laboratory exercise development. A total of eight proposals were developed into laboratory exercises. A sample of developed exercises included a Can Project that examined radiation heat transfer by use of different color cans exposed to the sun for a period of time; a Koozie project that examined insulation effectiveness of different materials used for cold drinks in cans; a bucket experiment that studied fluid dynamics using Newton's second law; and a pressure gradient of a fluid with a rotating cylinder that examined behavior of liquids with different viscosity and density spun at the same angular velocities. An example student idea generation by the Team Bucket follows:

A.) Eric – Refrigerator efficiency based on capacity. How much less energy would a full refrigerator require to maintain the same temperature as an empty refrigerator?

B.) Jim – Wing design (turbulent vs. laminar flow)

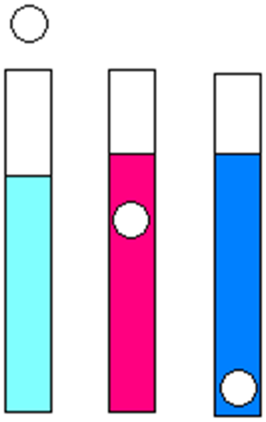






C.) Alex – Bucket Race Experiment

D.) Ginny – 1.) Viscosity measurement dropping balls in different weight fluids.

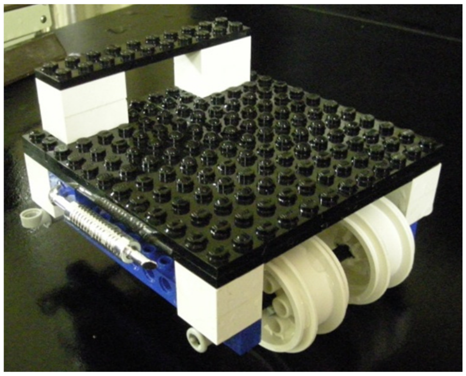


2.) Pressure cooker – measure end amount of liquid after boiling, compare with calculations.

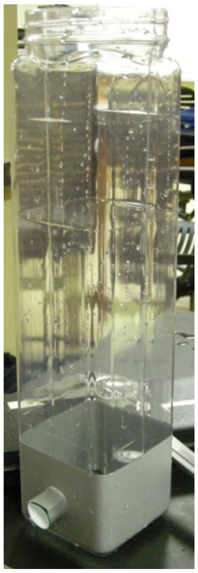
As seen above, team members proposed an experiment for approval by teammates. While team members had been asked to present one topic each, Ginny presented two – viscosity and the pressure cooker. Ginny said she just felt empowered to investigate whatever she wanted and this was her opportunity to do so. After team discussions, students settled to implement the Bucket Race Experiment citing reasons below for their choice:

"This experiment was chosen for a couple reasons. One reason is that one of the fluid dynamics professors referred to a *similar setup multiple times* in class and even included a similar problem on homework and tests. Another reason is that this experiment can be done by students of *various learning levels*. High school students could perform this experiment and use Newton's second law to calculate the work done. Whereas, more advanced college students could do the experiment and use Bernoulli's equation and Newton's second law to solve for the hole location and diameter that would provide for the maximum amount of distance traveled. Additionally, this experiment was chosen because it is an experiment that all the members of the team would not mind performing as a *class enrichment* project."

The operating theory cited: "This experiment is almost ideal for describing Newton's Third Law which says that for every action there is an opposite and equal reaction. The first action is the release of the energy and mass of the water in the container and the reaction is the movement of the container on its cart in the opposite direction. The only flaw is that there is likely to be a significant amount of friction hindering the movement of the cart and therefore it does not seem to have an equal reaction."



The Cart



The Bottle

Student sample calculations:

1. Find the **theoretical** amount of work performed on the system using the amount of water released.
    a. Calculate the initial center of mass of the water
$$h_o = \frac{h_{water} - h_{hole}}{2} = \frac{0.273050\ m - 0.018288\ m}{2} = 0.127381\ m$$
    b. Assume the final center of mass is at the bottom of the hole
$$h_f = 0$$
    c. Calculate the change in height of the center of mass (D_{drop}).
$$D_{drop} = h_o - h_f = 0.127381\ m - 0\ m = 0.127381\ m$$
    d. Calculate the amount of force exerted by the water.
$$F = ma = (1.393\ L)\left(1\frac{kg}{L}\right)\left(9.81\frac{m}{s^2}\right) = 13.665\ N$$
    e. Calculate the total amount of work done over the average distance measured from trials 1-3.
$$W = Fd = (13.665\ N)(0.127381\ m) = 1.741\ J$$
    f. Calculate the total amount of force required to propel the system the average distance measured.
$$W = Fd \rightarrow F = \frac{W}{d} = \frac{1.741\ J}{2.17805\ m} = \boxed{0.7993\ N}$$
2. Find the **actual** amount of work performed on the system using the given force equation and height of the water.
    a. Calculate the amount of force using the velocity of the water leaving the hole that can be calculated from the volumetric flow rate found previously. Obtain an equation for force with respect to height.
$$\bar{F} = \rho V_{hole}^2 A$$
$$\bar{F} = \frac{\rho \forall^2}{A} = \frac{\left(999\ \frac{kg}{m^3}\right)(1.674\ x\ 10^{-4}\ \frac{m^3}{sec})^2}{\frac{\pi}{4}(0.018669 m)^2} = 0.1023\ N$$
    b. Calculate the total amount of work done over the average distance measured from trials 1-3.
$$W = Fd = (0.1023\ N)(2.1781\ m) = .223\ J$$

Authors views: Students were not offered a series of experiments to conduct each week as is typical in structured/canned experiments but were offered a time to create their own experiments. Students' realization that they had to develop an idea into reality within given constraints seemed to make them ignite their organizational method skills, teamwork efforts, and mastery of a subject matter in a specific area. Using Team Bucket as an example (could be applicable to any other team), it is observed that they first developed a Gantt chart for their activities. Next, the team identified strategies that would help them do their work efficiently, these included learning/reviewing the theory of their selected topic, governing equations, procuring materials, and setting deadlines. The commitment to produce a well developed experiment caused them to own their experiment. Ownership of the experiment design seemed to have put energy in the effort of learning and reviewing relevant materials. The teamwork effort seemed to flow seamlessly since the team had made division of labor among themselves. Authors viewed strengths of the open approach to include but not limited to student mastery of specific concepts in greater detail, development of organizational skills, development of teamwork skills, and design and development of a product that worked and operated within a given theory. On the other hand, the weakness seemed to hinge on limited class time. Students routinely remained in class to work on their projects even when the session was over. Many came during their free hours to continue with their work.

Results

An instrument was developed to capture student experience. This instrument was evaluated by several faculty members to ensure capture of useful information. Five open ended questions were developed and five Likert-type questions made the instrument as shown in the appendix. The open ended questions were designed to evaluate the effect of the course on students' mastery of the concepts, have them describe and assess their ability to synthesize concepts in the designed experiment, and provide an opportunity to make suggestions for improvement.

A summary of responses to the open ended question is provided in Table 1, while the Likert results are given in Table 2. From Table 1, it is evident students felt the experience enhanced their mastery of the subject matter (see summary of answers to questions 1, 2a, and 3). They also indicated a significant level of preparation and planning (question 5). As predicted by Aristotle and proponents of active learning, students easily made the connection between an increase in ownership of the process (or more doing) and an increase in understanding. In addition, students appeared to have made the connections between concepts required for transfer and practical application. For example, responses to question 4 (regarding considerations for their experimental design) included an understanding of the importance of "practicality and purpose" and the need to "synthesize" the work from team members. Finally, responses to question 2b (disadvantages to active learning) and 6 (suggestions for improvement) indicate that time was a significant constraint to the process. As discussed previously, time is a significant factor in learning. Active learning can appear more time consuming than traditional methods, but this is likely because students rarely are given sufficient time to acquire the process and epistemological skills they need to be successful practitioners. Students highlight the recurrence of 'unforeseen problems,' 'uncertainty,' and 'unexpected errors.' In fact these are not atypical issues encountered by engineers on a daily basis, yet traditional classroom activities often circumvent such issues, giving students false expectations. At the same time, open assignments require students to resolve these issues, improving their understanding and application of the underlying concepts.

Table 1: Summary of Survey answers and identified themes

Question	Summary of Answers - 2008	Summary of Answers - 2009	Themes
1. **In what way did this course enhance your learning of thermodynamics, fluid mechanics, or heat transfer?**	• Finally put into practice equations • Apply concepts to real life • Forced revisiting course material	• Understand heat transfer • Reinforce theory and calculations • Experiment yourself	• Application of theory into practice • Better understanding of concepts
2a. What do you consider advantages of active learning	• Room for creativity • Interest and excitement for class • Understand problems before fixing • Ownership of work	• Involved more and interesting • Personal investment • Sense of accomplishment	• Freedom of exploration • Ownership • Deeper understanding
2b. What do you consider disadvantages of active learning	• Time consuming • Less structure • Unforeseen problems	• Takes more time • Unexpected errors and challenges	• Time issues • Uncertain of potential problems
3. How do you compare canned laboratory exercise vs. active learning process	• Canned – dull; poor job to provide useful information; going through the motions • Open – help develop ideas; interesting	• Canned- performed without fully understanding; • Open- interactive; more design process; more challenging	• Canned – routine with less learning • Active- challenging; more involved; better learning
4. How did the fact that you were developing an experiment for others affect what you learned and how you considered your design?	• Practicality & purpose very important • Think needs for class • Use more clear explanation	• More attentive in process & record keeping • Develop best possible exp. • Challenged to simplify	• Sought meaningfulness • Sought to synthesize team work
5. What type preparation did you do prior to conducting your experiment?	• Extensive planning & hypothesis • Study fundamentals • Research on lab testing equipment	• Thought through process • Calculated theoretical data • Account for unknowns	• Study • Thought through • Made predictive analysis
6. What would you suggest for improvement of the course?	• More time for experiments	• Need longer lab sessions	• More time needed

Table 2 shows again students on average agreed that the unstructured active learning course challenged their thinking beyond typical style problems. They also recommended active learning be incorporated into other courses. This was true for both offerings. Students from 2008 course also agreed or strongly agreed that the course enhanced their understanding of the concepts; those from 2009 primarily agreed though at least a few students were neutral.

Table 2: Summary on the Likert-type questions

	2008 (means)	2009 (means)
1. Better understand concepts	4.13	3.88
2. Challenged my thinking process	4.50	4.38
3. Improved my ability to work in teams	4.50	3.89
4. Assignments required thinking beyond rote memory or finding answers in textbooks	4.38	4.25
5. I would recommend this type of learning to other engineering courses	5.00	4.63

Conclusion

The unstructured/open approach to the laboratory experience in Thermo-fluids lab was introduced to two groups of students in subsequent years. Each group self-formed teams who thought through ideas and picked one that they implemented and developed into a product that satisfied a theory in thermodynamics, fluid mechanics, or heat transfer. Students had a total of 12 weeks to take ideas and change them into products through an engineering design process. Student evaluations indicate that they took ownership of their experiment design and studied to master the theory behind the experiment. They were able to transfer the theory and made it practical through the development of the artifacts. Further they analyzed their work and compared their analytical predictions to the outcomes of the experiment. They were able to evaluate the differences in results and try to gain an understanding of the difference, if any. Last, they communicated their process of generating ideas through implementation and testing their projects.

As Aristotle concluded "…activity in a certain thing gives man that character…", the authors believe that deep knowledge and understanding is best acquired through an alternative approach to traditional "canned" experiments that tend to offer a series of experiments with minimal student ownership and investment. Canned experiments are better placed for the freshmen and sophomore courses when the effort to build foundational knowledge is underway. At the junior and senior levels, students have the sufficient mastery of prerequisite material to undertake unstructured laboratory activities which are much more effective in facilitating the transfer of concepts and skills into professional dispositions.

Authors believe the 2009 class was consistently more conservative in their evaluation than 2008 class. Either way the results indicate positive affinity and appreciation to the learning approach to the extent they stated that they would ask other students to take the course.

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Appendix

Instrument

410L: Thermo-fluids Laboratory

Please answer the following questions to the best of your ability. Your response will help the instructor in planning for future classes. Thank you.

Definition: Active learning is more than doing laboratory exercise routines; it is having the freedom to engage through a thought process from theory, design, execution, and reflection.

1. In what way did this course enhance your learning of Thermodynamics, Fluid Mechanics, and Heat Transfer?

2. What do you consider advantages and disadvantages of active learning (open ended) as have been done in this class?

Advantages (Strengths)-

Disadvantages (challenges) –

3. How would you compare canned laboratory exercises versus active learning process?

4. How did the fact that you were developing an experiment for others affect what you learnt and how you considered your design?

5. What type preparation did you do prior to conducting your experiment?

Please select below (circle a number to the right) a response that reflects your perception

Which of the statements below do you ***strongly agree (5), agree (4), neutral (3), disagree (2), strongly disagree (1)***

1. Thermofluids lab helped me better understand concepts in thermodynamics, fluid mechanics, and heat transfer 5 4 3 2 1

2. The laboratory assignments deeply challenged my thinking process in scientific and engineering decision making 5 4 3 2 1

3. The course improved my ability to work in teams 5 4 3 2 1

4. Assignments required thinking beyond rote memory or finding answers in textbooks 5 4 3 2 1

5. I would recommend this type of learning to other engineering courses 5 4 3 2 1