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Towards a Philosophy of Engineering Laboratories

Dr. Michael Robinson, Saint Vincent College

Michael Robinson received his Ph.D. in Mechanical Engineering from Penn State University. He is currently an Assistant Professor of Engineering at Saint Vincent College in Latrobe, Pennsylvania. His academic experience includes positions as an Assistant Professor of Engineering at Messiah College, and as a Visiting Lecturer at Ashesi University in Ghana. His research interests include autonomous vehicle pedestrian avoidance algorithms and the epistemology of engineering education.

Towards a Philosophy of Engineering Education Laboratories

Abstract

Most engineering educators agree that laboratories are a key part of the engineering curriculum, but there is less agreement about what labs are to accomplish. This ambiguity may be partially attributed to changing views in science more broadly about the role of experimentation and parallel changes in emphasis on lab education throughout the twentieth century. When laboratories are seen as practical necessities, their perceived importance decreases. At present, many are returning to the view that laboratories play a key epistemic role. This paper develops a role for philosophy in understanding the purpose of laboratories. Concepts from classical and modern philosophy will be related to undergraduate engineering laboratories. Plato's view of learning as recollection will be used to suggest stages of understanding in a laboratory. John Henry Newman's concept of real assent will be presented as a key purpose for the laboratory. Alfred North Whitehead's rhythm of education will provide guidance on where laboratories naturally fit in the engineering curriculum. Taken together, these sources will develop an answer to the question: what is the role of the laboratory in engineering education?

Aims of Experimentation in Science and Engineering Education

Feisel and Rosa observe in their seminal paper on engineering laboratories that "while there seems to be general agreement that laboratories are necessary, little has been said about what they are expected to accomplish" [1]. Although much important research has been done since the publication of that paper in 2005 on the methods of engineering laboratories, research continues to be scarce on the purposes of engineering laboratories and the kinds of knowledge students are expected to acquire in laboratory settings; however, literature from adjacent fields like physics and chemistry is more developed in this regard.

Zwickl et al. present an instrument known as the Colorado Learning Attitudes about Science Survey for Experimental Physics (E-CLASS) [2]. In the E-CLASS, student responses to statements like "scientific journal articles are helpful for answering my own questions and designing experiments" or "when doing an experiment, I try to understand how the experimental setup works" are compared to expert responses. The data in [2] represent a wide range of institutions and show that, instead of laboratories improving epistemic agreement between students and experts, a small decrease in agreement is observed over the course of an introductory physics lab. This result is similar to another study which found that some laboratory experiences in basic electric circuits may deteriorate students' epistemic views, in particular their views about coherence of mathematical models and the physical world [3].

The literature from chemistry includes reflections on the purposes of educational laboratories. While chemistry programs in general devote more time to lab work than engineering, this has not led to greater clarity about the purpose of labs. Seery recently concluded about the current state of chemistry labs that "the literature is replete with proposed goals for inclusion of laboratory work, and as well as being extensive, these are often contradictory" [4].

Uncertainty about the role of experimentation in education can also be observed in science more broadly. Steinle investigated the history of experimentation in science and concluded that “the role of experiment as a tool for generating knowledge has been comparatively poorly studied” [5]. Given the long history of experimentation in engineering and science, the quotes above raise the question of why the role of experimentation remains doubtful.

Scientific experiments have been performed for millennia. Although it has been argued that ancient science had different goals than modern science, individuals like Aristotle still found a use for contrived experiments [6]. One famous example from Aristotle is an experiment to determine whether seawater is salty by nature, or whether it is fresh water with something added. He performed two experiments through distillation and filtering, both of which concluded that the salt in seawater is something that when removed produces fresh water.

Francis Bacon is often cited as the originator of the modern view of scientific experiments [5]. He assigned a high epistemic value to experimentation and advocated for experimental goals including “the production of new phenomena, the classification of these phenomena, and deciding between competing theories and hypotheses” [5, p. 408]. For hundreds of years the Baconian view persisted and experiments could be said to be almost synonymous with science. This paradigm continued until the 20th century when the role of experimentation was restricted from being the primary source of knowledge to being merely a practical means of testing theories. This trend has begun to reverse somewhat in recent decades and research on the philosophy of science is returning to the question of “how experiment and knowledge relate” [5, p. 409].

The rapid historical overview above indicates one reason why the role of experiments is uncertain; experiments have been perceived in different ways at different times. When experiments are seen as practical necessities, their perceived importance decreases, but when experiments are deeply tied to knowing itself, their perceived importance increases. Although the latter view appears to be gaining importance at present, the process of changing such opinions is often slow. The same trend just described in science can be observed in the history of experimentation in engineering education as well.

The early days of engineering education in the 19th century saw heavy emphasis placed on laboratory instruction [1]. Both theory and the laboratory were considered essential. This dynamic changed following World War II. In 1955 an influential document known as the Grinter Report “determined that the engineers being produced were too practically oriented and were not sufficiently trained to seek solutions by referring to first principles” [1, p. 122]. The recommendations of that report were gradually adopted and “some schools elected to minimize laboratories, citing the Grinter Report’s conclusion that knowing theory was paramount.” The result was that “many engineering schools began graduating engineers who were steeped in theory by poor in practice” [1, p. 122].

Accreditation requirements during the 1980’s and 1990’s were in part responsible for a renewed emphasis on engineering laboratories. In 1997 ABET adopted the Engineering Criteria 2000 (EC 2000) standards [7]. These included a set of eleven student outcomes, sometimes referred to as the a-k criteria based on the way the list was labeled. The second outcome on this list (outcome

b) addressed experimentation stating that students must have “an ability to design and conduct experiments as well as to analyze and interpret data.” [7] While this does not explicitly require laboratory instruction, this objective provided some impetus to institutions to improve their laboratories.

The a-k student outcomes were in place for roughly 20 years when they were replaced by the current set of seven student outcomes. While the current outcomes can be roughly mapped to the a-k outcomes, they include several significant changes. Outcome 6 now addresses experimentation and requires students to demonstrate “an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions. [8]” Comparison to objective b from the a-k criteria shows that a major component was added to this outcome – that students must demonstrate engineering judgement in drawing conclusions for experiments. This is significant due to the strong emphasis placed on engineering judgement by working engineers who cite such judgements as the ultimate guide to design decisions [9]. The inclusion of engineering judgement in this student outcome, and nowhere else explicitly in the outcomes (except for possibly a reference to judgement in outcome 4 which deals with ethics) gives an indication of ABET’s views about the purpose of laboratories as going beyond practical necessities. It seems that experiments form a key part of the engineering way of knowing.

Laboratories and the Engineering Curriculum

Laboratories are one of three major modes through which engineering education is delivered along with engineering theory which is often delivered through lecture and assignments, and design projects. These modes are not all together distinct as will be seen by considering an example. A course in fluid mechanics will present theory related to pumps and flow in pipes. Learning is often evaluated by analytical problems with one correct solution. On the other hand, a design project may use the same ideas in the service of creating a drinking-water system, or a fire-fighting robot. Such projects have many possible solutions and involve criteria beyond the transport of water. Assessment in design is usually based on effectiveness at meeting design criteria. Successful designs may be reached though calculations, but other solutions paths which meet all objectives can also be valid. Even when calculations are performed, discrepancies between actual performance and theory are rarely investigated if the solution meets its objectives. A laboratory on fluid flow sits between the two modes just described. A fluid flow experiment will almost certainly involve calculations based on theory and those results are compared to the performance of a practical system. This example illustrates the role of the laboratory as a bridge between theory and design. Despite the importance of this role, being situated in a middle position means any expansion to theory or design may come at the expense of the role of the laboratory. This is particularly likely when laboratories are seen as fulfilling certain objectives. Once a list of objectives has been created, it is natural to ask whether those objectives might be more efficiently addressed elsewhere.

Objective overlap from both theory and design in the engineering curriculum is another cause of doubt about the role of the laboratory. For example, Faber and Benson used a homework assignment to assess student epistemic cognition in a biomedical engineering course which has significant overlap with laboratory objectives. The assignment required students to consider a range of factors and empirical data to determine “the combined effects of strain rate and age on bone strength of a 90-year old subject compared with a 20-year old" [10, p. 704]. Answering this problem involves evaluation of models and analysis of data to draw conclusions, which are key lab objectives from [1] and are also the laboratory objectives faculty rated highest in importance in [11]. Design projects also overlap with many laboratory objectives including (using the language of [1]) design, learning from failure, creativity, teamwork, safety, and communication.

The most unique laboratory objectives of Feisel and Rosa [1] are more practical in nature including experimentation, instrumentation, and psychomotor. There is some evidence that these objectives are less valued by faculty as these objectives were rated below median importance by the faculty in [11]. Ethics in the laboratory was the only distinct laboratory objective in Feisel and Rosa rated of high importance by the faculty in the Australian National Engineering Laboratory Survey and this topic has received little attention in the literature. For example, between 2003 and 2023, only two papers in the ASEE PEER repository have titles or tagged topics including both ethics and laboratory.

The discussion above indicates another reason for uncertainty about the role of laboratories. Many lab objectives overlap with the other modes of engineering education, and it may seem beneficial to let other modes perform roles attributed to laboratories in the past. It has also been shown that the most unique (and practical) laboratory objectives are not highly valued by some measures of faculty perceptions.

Although thinking in terms of objectives has many benefits for learning, constructing an education around objectives in not without drawbacks, particularly for laboratories. The biggest problem with objectives is that it is very difficult in practice to separate student performance in the lab into discrete objectives. For example, if students are to accurately analyze data and compare with theoretical models, they must understand the details of the experimental procedure and instrumentation that produced those data as well as the assumptions and limitations of the theoretical models. Laboratory experiments include complex problems with many sub-parts and dependencies. It is difficult to set boundaries on what information may be relevant to interpreting experimental results which necessitates the use of engineering judgement. It is also difficult in practice to determine from a student's lab report exactly what abilities they have demonstrated.

The history reviewed here shows a periodic change in perceptions of the purpose and consequent importance of laboratories in both engineering and science more broadly. While there is a clear practical benefit to experimentation, there is also a sense that something beyond practical necessity is key for understanding the role of experimentation. This conclusion was further developed by investigating the role of the laboratory within the engineering curriculum. It was argued that the laboratory has a middle position between theory and design, and that this position is somewhat precarious. It seems possible that the important aspects of the laboratory could be absorbed into other modes of engineering education leaving only practical skills training for the laboratory; however, this arrangement does not seem entirely satisfactory either. The need to explain why laboratories are important and what students might learn in a laboratory motivates a turn toward philosophy. Concepts from both classical and modern philosophy are explored below to suggest what happens when students learn in the laboratory, what purpose may transcend the practicality of laboratory learning, and where laboratories naturally fit within the curriculum.

Philosophy and the Engineering Laboratory

Plato's account of learning as recollection may seem unusual on first hearing; however, it will be argued that recollection provides a model for the process of learning that should take place in the laboratory. The theory of recollection holds that learning is not the process of knowledge coming from the outside into the mind, but rather the recovering of something an individual has always possessed but which was previously unrecognized. The review of recollection that follows is largely based on Jones's dissertation [12]. Plato explores recollection in three dialogs – the Meno, the Phaedo, and the Phaedrus. The Meno introduces this idea of recollection through something like an experiment in which Socrates leads one of Meno's slaves, who has never studied geometry, to recall the side length of a square with an area of eight square feet.

The Meno account reveals three stages of recollection which apply to all learning but are particularly suited to experimentation. These stages are the rejection of false opinions, the establishment of true opinions, and finally the acquisition of knowledge. The Meno account begins with Socrates demonstrating to the slave that a square with a side length of 2 feet would have an area of four square feet. Socrates then asks the slave what side length would give an area of eight square feet. The slave shows he has several false opinions by answering first that the side length would be twice two – or four feet. On being made to realize this is incorrect and gives an area of sixteen square feet, the slave changes his answer to a side length of three feet, which is also shown to be incorrect. The slave then admits that he does not know the answer. This is the first stage of recollection – the rejection of false opinions. This stage is essential for the learner, not only because he can let go of false opinions, but primarily because he now sees why his previous opinions were incorrect, which is valuable knowledge in itself. Socrates continues his work of questioning the slave until the point where the slave recollects the correct opinion that the diagonal of a square with an area of four square feet is the side length of a square with an area of eight square feet. The slave in the Meno ends his experience of geometrical recollection in the second stage of recollection – true opinion. He has seen something, but "the slave's current grasp of the truth in the state of true opinion is 'dreamlike' and hazy… the state of knowledge is implicitly suggested to be one of greater clarity and understanding" [12, p. 100]. In the final stage of knowledge, the individual can give a precise causal account of the knowledge he or she has.

Removing false opinions is a crucial role of laboratories. This is especially true of scientific experiments where a mistaken hypothesis is rejected based on an experiment, and it should also be true of educational laboratories. Current engineering education pedagogy recognizes the need for students to come to the lab prepared, but this is very challenging to achieve in practice. While the basic theory of a lab can be reviewed briefly at the start of the session, labs often use a variety of theoretical and procedural knowledge about which the students may be mistaken. Despite efforts to make sure students are adequately prepared for a laboratory, it is inevitable that false opinions will remain, and this is an important pedagogical role for laboratories. More opportunities should be available for students to record their opinions, whether they be true or false, in preparation for lab and to allow the experiment itself to correct those opinions as in the recollection account. This assumes that students see the experimental results as the true account and not the theoretical calculation; otherwise, students may try to modify their experiment to make it agree with the theory in an unsuitable way.

At present, it seems that the best-case scenario for student laboratories is that they end in the second stage of true opinion. After completing the lab they know what the answer should have been, but their knowledge is still "dreamlike and hazy" [12, p. 100]. As students move through an engineering program, they should be advancing towards the final stage of recollection of true knowledge where they can give a causal account of the knowledge they possess. This appears to be in keeping with ABET's current student outcomes which require students to use engineering judgement to draw conclusions [8].

Another application of Platonic recollection to laboratories is the role of the senses in coming to knowledge. While Plato's recollection dialogs expressly deny the possibility of "learning through the body," they also hold that although the senses are not a cause of true knowledge in recollection, they are "a necessary epistemological precondition for the intellect to begin to conceive of something's intelligible nature" [12, p. 92]. The educators in [11] ranked the importance of sensory awareness in the laboratory as roughly median for the objectives assessed, but perhaps this role of laboratories should be more highly valued.

While many may doubt the reality of recollection as an explanation for learning, this theory does capture the fact that there are many aspects of learning which evade a precise definition. This seems particularly true in the laboratory where human judgment must be applied to draw conclusions. We can never fully explain human judgement. At best, we can classify different ways we reach conclusions. This classification was taken up two millennia after Plato by John Henry Newman in his work *Essay in Aid of a Grammar of Assent* or more succinctly, *The Grammar of Assent* [13]. Newman's concept of real assent will be put forward below as a fitting goal that takes engineering laboratories beyond immediate practical aims.

The first distinction made by Newman in *The Grammar of Assent* is between inference and assent. Inference is an acceptance of the truth of a proposition based on certain conditions, such as "if x and y are true, then z must be true." Inference is the weakest form of acceptance for Newman because it rests on conditions, and the truth of those conditions may not be knowable. This form of acceptance is based on logic, but clearly does not include the full scope of human judgements including engineering judgement. Inference is contrasted with assent which is the main topic of *The Grammar of Assent*.

Assent to a proposition may be based on many pieces of evidence, but unlike inference the certainty of assent goes beyond the limitations of strict logic. Assent is classified by Newman as notional assent when the object of assent is an idea or abstraction. Newman illustrates notional assent by the example of a boy who assents to the proposition "lucern is food for cattle" because his mother told him so. This can be true assent even if the boy does not know what lucern is, but simply based on the trust he has in his mother. Notional assent is contrasted with real assent where what is assented to is a thing itself. An example of real assent would be if the boy in the example above sees cows in a field grazing on lucern. The same distinction is important in engineering studies. Most engineering students give at least notional assent to their studies. They trust their professors even if they have no real experience of the things discussed in class. For example, a student in an instrumentation class may be told that two dissimilar metals brought into contact and heated at their junction will produce a voltage that can be used to measure temperature. It is unlikely that a student has experienced this phenomenon, but they can, and presumably regularly do, give notional assent; however, if the student has put two metals together, heated the junction and observed that the voltage does indeed change they are at least moved towards real assent.

Both notional assent and real assent have benefits and limitations. Newman describes how “to apprehend notionally is to have breadth of mind, but to be shallow; to apprehend really is to be deep, but to be narrow minded… however, real apprehension has the precedence, as being the scope and end and test of the notional” [13, p. 34]. If we insisted on observing everything for ourselves, there would be little we could know, but without some element of real assent, our knowledge remains superficial.

Real assent has a clear connection to the laboratory, but the importance of trying to make concepts real in the laboratory is debatable. Critics of applied modes of learning often point out inefficiency in such attempts. For example, when commenting on the state of lab education as a tool for teaching theory, Ausubel asserts that students “wasted many valuable hours collecting empirical data which, at the very worst, belabored the obvious, and at the very best, helped them re-discover or exemplify principles which the teacher could have presented verbally and demonstrated visually in a matter of minutes” [14]. The distinction between real and notional assent is key for addressing this kind of critique. It is not argued that real assent makes students learn more; as Newman says above, notional assent has the distinct advantage of breath. The importance of real assent is that the personal experience of a thing exerts a force on the mind and will that does not exist with abstractions. Newman says “acts of Notional Assent and of Inference do not affect our conduct, and acts of Belief, that is, of Real Assent, do (not necessarily, but do) affect it” [13, p. 90]. Put succinctly, real assent moves us. At some level, the highly abstract nature of engineering theory needs to be grounded in real assent. Studies of practicing engineers show that the ability to connect abstractions to the physical world is key for forming engineering judgement [9] and this same experience needs to be a part of engineering education.

It will not be argued that all laboratory exercises lead to real assent, or that only the laboratory can produce real assent. Newman says that real assent is “of a personal character, each individual having his own, and being known by them. It is otherwise with notions; notional apprehension is in itself an ordinary act of our common nature” [13, p. 83]. The fact that real assent is highly personal means that it cannot readily be systematized and predictably delivered to students, which is a challenge for the acceptance of real assent as a goal of laboratories. It is also possible that lectures may produce real assent either through videos, demonstrations, or through appeals to previous experiences of the students. Nevertheless, the depth of exposure available in the laboratory provides an ideal environment for fostering real assent and attaining the positive motivational results outlined above which occur when we apprehend concepts in a real way.

The potential of real assent for motivating knowledge acquisition and knowledge application raises the question of when laboratories should be deployed relative to the presentation of concepts in lecture. Current practice suggest that the teaching of a theory comes first followed by a laboratory that applies and explores the limitations of that theory. While there is a clear reason for this order, might it not make sense at times to have the lab precede the theory? This would have the advantage of following the order of most discoveries where regularities in nature are observed first and later codified into a theory. An additional benefit of labs preceding theoretical descriptions is that it may provide opportunities to apply Alfred North Whitehead's theory about the rhythm of education.

Whitehead's rhythm of education is a way of describing the natural stages of learning [15]. We begin with the stage of romance, or "excitement consequent on the transition from bare facts to first realisations of the import of their unexplored relationships" [15, p. 18]. We then proceed to a stage of precision where we learn "a given way of analysing the facts, bit by bit" [15, p. 18]. This is followed by the stage of generalization when the ideas developed in the precision stage are explored in different settings. Whitehead describes generalization as "a return to romanticism with the added advantage of classified ideas and relevant technique" [15, p. 19]. Because these stages are for Whitehead the way we naturally learn, Heywood describes the rhythm of education as a theory of motivation [16].

Labs may be made to fit the precision stage as that mode often dominates the engineering curriculum, but they would be more fruitfully conceived of as generalization or even romance in the terminology of Whitehead. Generalization may even be achieved in a lab where experimental results closely align with theory which at a minimum provides some application of theory and would have the added benefit of moving a student towards real assent. On the other hand, it would be more helpful for labs as generalizations to show how a theory may explain certain behaviors, but not others, leading a student to understand the need to qualify theory and gain further knowledge. In addition to their role in the generalization stage, labs may also occasionally be put to good use in the romantic stage where an idea can be seen before it is analyzed in a detailed, systematic way. It is likely difficult in practice to design labs that function as authentic experiences in the romantic stage and not as contrived exercises that waste time as noted by Ausubel [14]. Although entire labs may be designed in the romantic stage, perhaps it is better if some key observations of one laboratory suggest concepts to be explored later in lecture. If successful, such experiences would fill a needed and often lacking stage in the rhythm of engineering education.

Conclusions

This paper has aimed to deepen understanding of the purpose of engineering educational laboratories. The history reviewed above showed that perceptions of experimentation have fluctuated significantly over time. When experiments were seen as key elements of human knowing, such experiments were highly regarded; when experiments were seen as practical necessities, their importance lessened. It appears at present that there is a growing awareness of a broad importance for the laboratory. It was argued that learning objectives alone do not provide a distinct purpose for laboratories since objectives are often shared with other modes of engineering education like analysis problems and design projects. The benefits of laboratories in teaching students engineering practices also does not seem a sufficient purpose as such immediately practical objectives are not as highly rated in importance by engineering faculty as other conceptual objectives. These factors suggest that a philosophical basis is needed to provide an understanding of the broader role of the laboratory.

Three philosophical concepts were related to engineering experimentation. It was argued that laboratories should take their structure from Plato's conception of learning as recollection.

Students should advance through the stages of discarding false opinions, developing true opinions, and finally attaining true knowledge by being able to give a causal account of their knowledge. A purpose beyond practicality for the laboratory is found in John Henry Newman's concept of real assent. Labs should not aim to teach theory; that goal is better served by other modes of engineering education; rather labs provide the opportunity (although not certainty) for students to apprehend engineering in a real way which has the power to deepen knowledge and motivate action. Finally, Whitehead's rhythm of education was applied to laboratories, which seem most useful in the generalization stage, but which also could play a key role in creating a stage of romance in engineering education.

Developing practical labs which do the things described above is a difficult task. The majority of students' engineering education follows the pattern of a theory being presented followed by calculations based on that theory. Although this mode of instruction has clear importance, it is not the same as the Socratic process of learning advocated above. Students may have little experience learning through questioning and may be unwilling to revise their false opinions in response to data collected in the lab, preferring to revise experimental results to fit a theory instead. Experience also indicates that students may not value real assent when notional assent has sufficed for so much of their education. A single lab experience will be unlikely to produce much benefit; however, if such experiences are spread throughout a student's college education, it is anticipated that student behaviors and perceptions will change.

The author's home institution created laboratories across several courses based on the ideas above which culminate in lab taken in the spring of junior year which integrates concepts from several courses. Since this is the last laboratory in the curriculum, students are expected to show proficiency in experimentation and the ability to correctly apply material from past courses like statics, circuit analysis, and thermodynamics. Minimal instructions are provided since all the equipment has been used by students for several years. An example assignment is shown in the appendix. Experience indicates that many students come to this experiment with false opinions about fundamental engineering principles. Although a brief review of mechanism analysis is provided when this lab is introduced, students need to determine if their analysis matches their experimental results. For example, although the pneumatic cylinder in this experiment is at a slight angle when fully opened, students often assume it is vertical. This leads to a significant discrepancy of 40 to 60 percent between their experimental measurements and their calculations. While some groups succeed in moving beyond false opinions, many do not persist in finding the cause of this discrepancy. Future research involves assessing to what extent labs like the one presented here address the other ideals presented above, such as developing real assent in students.

Assessing the principles above will likely involve developing new research methods. For example, instruments are needed to determine how effectively labs aid students in discarding false opinions, how levels of knowledge like true opinion and true knowledge can be distinguished, and most importantly, how students develop real assent in the laboratory. In the short term, it is anticipated that the categories provided by the philosophy reviewed here may provide new perspectives and new terms for educators to discuss potential improvements to the engineering laboratory experience.

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Appendix: Example lab assignment on mechanism analysis

Background: Pressurized cylinders are often used as supports in applications like vehicle hatches and hoods. You are provided with a SOLIDWORKS model of the mechanism shown below on the right. Use the dimensions from that model and your data on the pneumatic cylinder from lab 1 to perform the analysis below.

Experiments:

1. Calculate the force applied by the cylinder on the load cell in the fully-opened position. Confirm with an experiment.
2. Calculate the pressure needed in the cylinder when it reaches 30 degrees to allow this mechanism to rise on its own. Confirm with an experiment.

Performance Indicators	**Meets Expectations** 2	**Developing** 1
Develops experimentation *Creates effective experimental plan*	Experimental plan includes ways to verify measurements	Creates a reasonable experimental plan
Analyzes data *Performs necessary calculations*	Calculations are correct or contain only minor errors	Calculations contain significant errors
Interprets data *Presents and explains information*	Data presentation and explanations are adequately complete and facilitate comprehension	Data presentation and explanations are incomplete or difficult to interpret or follow
Uses engineering judgment to draw conclusions *Evaluates experimental validity*	Provides adequate assessment of experimental validity	Provides minimal assessment of experimental validity