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Lasting Laboratory Lessons

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Lasting Laboratory Lessons

Abstract

As stated by Alexander Pope, "*A little learning is a dangerous thing*." Scientists and engineers will readily attest, a superficial knowledge of the theory can make us think we have more expertise than we really do, and thus at best will make us to look foolish and at worse cause tragic consequences. This paper describes the experience of a student who is able to perform well in courses in the physical sciences and engineering as indicated by grades, but who completes this education with only a shallow understanding of the subject. For the student, there remain gaps between theory and practice, and numerous assumptions necessary for a deep understanding are missing. We offer a solution to this problem in the form of a new approach to lab courses that emphasizes relevancy to the student and student participation in devising the lab. We maintain that labs designed with these two elements in mind, along with a set of guiding principles we discuss, increase the likelihood of deep and lasting learning in the student. We close with a proposal to implement labs of this nature not only in engineering and physical science courses, but in certain mathematics courses as well, with the intention of deepening student learning and retention of mathematical concepts.

The Problem: Shallow Learning

"*Education's what's left over after you've forgotten everything you've learned.*" James Conant

As an undergraduate physics major, the first author took several lab courses, followed the instructions and was assigned good grades. He spent little to no time reflecting on each lab afterwards, instead going on to focus on the next problem set, paper or upcoming exam. While the labs were often designed to demonstrate theory that was introduced in lecture, there were many situations in which important underlying assumptions were not mentioned. Now, as a mathematics professor teaching courses with applications, such as differential equations, discrete mathematics, and linear optimization, the author's interest in applied topics has been rekindled. It is apparent that his learning in undergraduate lab courses and the supporting lecture courses was not sufficiently deep and did not include the totality of the necessary theory required to make a circuit work or even to explain its operation. In some ways, the author was the teacher's worst nightmare: he and his professors may have thought the learning was going well as indicated by the grades. But in reality, he was merely successful in imitating procedures to obtain results without any deep grasp of what was actually occurring.

The second author, observed a similar phenomenon, except in the area of implementing a prototype. The prototype would be designed and implemented using the requisite theory and accepted practices, but when "turned on", it rarely worked. After some minor tweaking, it finally worked. At first glance, the prototype's implementation was almost exactly the same before and after the adjustments, but again, minor changes were required to make it fully operational. The presuppositions that went into the design and implementation were insufficient to achieve functionality.

There is some recognition of this problem in the literature on engineering laboratories. Feisel and Rosa [1] point out the lack of consensus on what constitutes proper laboratory instruction and the overall lack of consensus on what constitutes an appropriate laboratory experience. They decry the dearth of literature on learning objectives associated with instructional engineering laboratories. In any earlier paper, Ernst [2] proposed as objectives that students "should learn how to be an experimenter", that the lab "be a place for the student to learn new and developing subject matter", and that the lab course "help the student gain insight and understanding of the real world". As indicated above, this was not our experience in general. Ernst was aware that labs were not achieving their goals, pointing to symptoms such as an "apathy" in many students towards labs and a lack of resemblance between the tasks carried out in the labs and the real world. Since linking the real world to theoretical knowledge gained in lecture is supposed to be a goal of laboratory courses [1,2], this symptom is particularly troubling.

In the book *Shop Class as Soulcraft* [2], Matthew Crawford writes "…science adopted a paradoxically otherworldly ideal of how we come to know nature through mental constructions that are more intellectually tractable than material reality, hence amenable to mathematical representation."[1] The theory we learned in undergraduate courses could represent reality compactly and elegantly with mathematical notation (e.g., kinematics, electricity and magnetism). Yet often times, even in electrical systems where often accurate models can be developed (e.g. SPICE circuit), it seemed divorced from reality. We were taught that an object traveling with a constant velocity exerts no force. Although obvious, it still took us a while to reconcile how a crash could cause damage if the vehicle was travelling at a constant velocity. Partly this was a failing of not thinking through the hand-off between the model and reality. But this kind of question was simply outside the curriculum. We were never asked questions like this in class, on homework assignments, exams, etc. What we were asked was to solve certain kinds of problems using the theory. We found that most problems could be solved neatly by the theory. Neatly doesn't mean quickly or without tedium or clever mathematical tricks. It simply means without ambiguity, and without having to introduce additional assumptions into the problem. As youngsters, we thought the way the universe worked was some complicated mystery, understood only by grown-ups, or the experts. In high school and college science classes, we learned many explanations for how things worked, but something was missing. The sense of explanation often felt like: "Well, you can't really understand reality as reality." Instead we talked about this abstracted version of reality in which these models work well. And somehow, in applying these models to reality, the bridge between the abstract and real situations is crossed. But exactly how this happened did not seem to be as important an educational outcome as facility with the abstract models.

After finishing up the physics major, the first author also found his skills were lacking in the hands-on practical application of what was learned. For example, in attempting to build an electromagnetic telegraph device many years after college, he encountered issues in which the voltage of the battery voltage output was lower than expected. With help from the second author, he learned the problem was due to the relatively high internal resistance of the battery. This is a case where the model was insufficient to describe reality, presuming that a battery was an ideal voltage source. This was a concept hardly mentioned in the coursework. The author went back to the physics text book and did find a brief explanation that a battery does indeed have internal resistance. There were even a couple of exercises to reinforce the explanation. The theory and the exercises all assumed the battery's internal resistance was known and then led the student to calculate the actual voltage drop over the circuit factoring in the battery's internal resistance. But for a real circuit, the internal resistance is not readily known. There was no discussion in the text on how to find it either. While this problem was eventually solved and the telegraph became functional, there is a great deal of frustration that the author's prior education did not include these types of underlying assumptions. In the mathematical world, the assumptions that go along with a theorem are clearly stated and must always be checked. For example, the First Fundamental Theorem of Calculus about integrating derivatives requires that the function in question be continuous. Since the experiences recounted above, we have taken steps to address these issues of disconnect between theory and practice and potential for lack of depth in this type of education through a new approach to labs. This is discussed in the next section.

Towards a Solution: Relevant, Student-Devised Labs

What makes a learning situation deep and memorable? The two guiding principles for the kind of lab we propose are *relevancy* and *student involvement in devising the lab.* There can be many other factors in designing labs, some of which we list in the next section, others of which can be found in the literature in works such as Feisel and Rosa [1] and Ernst [2]. But given our experiences, we see *relevancy* and *student involvement in devising the lab* as central. This type of proactive student engagement in their learning is supported in the works of Olin College [3], and Montoya et al. [4].

Relevancy. When a lesson connects to something in a student's life (past or present) or their aspirations for the future, their intrinsic motivation will be activated. They participate in the lesson with greater interest than if only motivated by external factors such as grades. This increases the chances of something from the lesson being retained. A great opportunity exists to better integrate the various threads of the educational experience by creating labs that are relevant to students and that they have helped devise. The labs are constructed around practical considerations that arise in applications of interest to students.

Consider “Experiment 1” on “Transients in RLC Circuits” in the first author’s undergraduate *Physics 231 A Laboratory Course.* In the accompanying lab manual, the “Experimental Procedure” section begins “The circuit you will use is shown in Fig. 1-3 with the square-wave output of a function generator to drive the circuit.” This set-up had no relevance to the author. What is this circuit? When had he seen one in real life? Is he likely to be using a function generator any time soon other than in lab experiments? If so, then how? If not, what in reality does it stand in for? Earlier in the manual, there was a clear presentation of the mathematical model for the circuit, culminating (through the solution of a differential equation) in expressions for the voltage on the capacitor under different values of resistance. The description even starts to link to real systems, pointing out that the *critically damped* case “is frequently a desirable property, especially in mechanical systems” and “gives the most rapid conversion of electrical to thermal energy”. But, *critically damped* is a technical term used by control engineers and sounds like something that might be memorable and worthy of additional explanation. Unfortunately nothing more on this topic is mentioned in the lab. Now, in retrospect, we see that most of the undergraduate science or basic engineering labs previously completed focused on illustrating fundamental laws (e.g., Kirchhoff’s Voltage Law) or properties of elements (e.g. transistors, Op-Amps) in circuits whose main purpose seemed to be the demonstration of such laws and properties, instead of a more functional purpose such as amplification.

So how does the student make the lab more relevant, especially if the topic is new? The instructor plays an important role in facilitation. Given the subject matter, the instructor should provide examples of applications that can serve as choices for the student to use in their lab or as inspiration for them to devise others. The applications can be extremely simple, such as a blinking LED or a tone from a speaker. These are things everyone has observed but likely has no idea how they work. In one case, the author had previously assembled a simple circuit sounding a rhythm on a speaker and wanted to amplify it. It was learned that a transistor could be used for the amplification and therefore, decided to try it out as a means to increase the volume. The “lab” was to learn how properly to configure the transistor in the rhythm circuit. Having the application in mind provided greater motivation and helped make the learning stick.

A similar situation occurred regarding capacitors. The first author remembered that capacitors store energy in the form of charge, and that the charge capacity was a function of the capacitor’s size and shape. Its voltage value was a function of time in conjunction with other elements connected to it. But it was not until pursuing an experiment several years later that he realized he had never really understood the purpose of a capacitor. In that experiment, the circuit consisted of a battery, switch, and a series resistor/capacitor. When the switch was on, the capacitor charged up. After removing the battery, the capacitor still kept its energy and he could see that it functioned as a type of temporary battery. Its energy storage function was reinforced, but more importantly, it started to resemble something useful. In a slightly more complicated circuit involving a relay, LED, and capacitor, he learned the capacitor storing charge was a way to slow down the oscillation of the relay. Thus the concept of the capacitor being an energy storage device was extended to that of an element also capable of slowing down an event.

Relevancy is characterized above primarily in terms of subject matter. Another form of relevance is in terms of mental models. "Anything is easy if you can assimilate it to your collections of models. If you can't, anything can be painfully difficult." wrote Seymour Papert in *Mindstorms* [6]. Papert points out that what an individual is capable of learning is dependent on the models he has available. This will be unique to each student.

Student Role in Devising Labs. We also maintain students should play a role in creating the learning situation. By doing so, students take *ownership* of their learning, specifically, figuring out *how* to learn *what they need to learn*. Our role is to facilitate this for them, so that they still end up achieving the intended outcome (e.g., learning how a transistor amplifies current in a circuit). Students come away with two benefits: (1) understanding of the subject matter at hand, and (2) developing the ability to self-learn. This is in contrast to labs predicated on imitation. For example, in the RLC lab described earlier, the stated objective was: "To observe the behavior of an RLC circuit in the absence of a driving voltage." According to the theory, the oscillation would eventually die out due to resistive losses. In conducting a version of this lab later on, we initially gave the students a specific procedure to follow. We then suggested that if some type of amplification device could be added, the oscillation might go on perpetually, like someone on a swing that keeps on going because the person continually adds energy to the motion. So students were then encouraged to add this feature so the oscillation would not die out. Here the students spent time figuring out how practical considerations, and assumptions come into play, and determining what data they need and how to find it, while at the same time, utilizing theoretical principles they have learned. Note also that our earlier objective is achieved in the somewhat open-endedness of the assignment, which allows students to make the lab more relevant to themselves by choosing a direction in which to take it. Perhaps this type of process of students devising labs starts off slowly at first with some degree of instructor facilitation. Maybe a full-class group activity occurs to hash out what the lab is going to be. But as the process unfolds, they should be given more of an opportunity to devise and take ownership of the lab. We expect this type of inquiry will lead to deeper, more permanent learning.

Returning to the resistor/capacitor circuit mentioned earlier, after the initial set-up and charging of the capacitor, the switch was then opened. A meter was set up to measure the capacitor voltage. A second resistor was placed across the capacitor and the voltage was seen to drop as the capacitor discharged through the resistor. Subsequently a variable resistor was incorporated so that with the turn of a knob, large changes in resistance could be incurred without having to rewire the circuit and thus the rate of voltage discharge from the capacitor could be more easily controlled. Swapping out capacitors of different sizes showed how the charge/discharge time also depended on the capacitance value. Looking back at old class notes, the notion of the time constant $\tau = RC$ was readily observed. The first author was able to come up with estimates of discharge timings using the theory and then test these by measuring with a multimeter. This was not unlike the steps in the labs he completed as a student. The key difference was that he was creating the steps himself. His satisfaction level completing his own steps was greater than following the recipe from previous years and will be long understood. If he were to forget the steps taken and results produced, he would at least remember that he could devise a process to demonstrate what there was to be shown.

In another example, the second author was taught in grade school that a transformer could only change time varying (AC) voltages. Being skeptical of the instructor, he took a 6 volt battery and connected it to the secondary side of a 120:6 VAC transformer hoping to produce a 120 volt signal. However, the theory stated that this would only occur if the source were AC, not DC and thus a battery would result in 0 volts on the primary side. However, it was observed that there was a brief surge in excess of 100 volts produced when the battery was initially hooked up. After going to the instructor, additional explanation was offered to show that an initial connection to a battery was in fact a time varying voltage, and therefore under these circumstances a transformer could momentarily increase a battery's voltage level. Skepticism of the instructor's statement led to an experiment which resulted in newfound knowledge of circuit transients, electromagnetic theory, and ways DC can be turned into AC. The assumption that a battery is a non-time varying source is not necessarily valid in all circumstances.

Reference to this type of lab building can be found in lab "Objective 3: Experiment" in Feisel and Rosa [1] in which students are expected to devise a complete experimental approach. It can also be found in the student-led curriculum development described in Montoya et al. [5]. Taken to its logical conclusion, the goal is what Papert referred to as "Piagetian learning" (after Jean Piaget) or "learning without being taught" [6]. It is akin to learning a language through immersion in a foreign land versus in a classroom. Students begin to build their own intellectual models. In our case, the instructor and potentially anything else in the student's environment supplies the building materials.

Additional Guiding Principles

These types of labs will be aided in fostering a deep learning experience if the following additional guiding principles are pursued: attentiveness, curiosity, humility, quality, gumption, robustness, skepticism, and problem-based. While having a different focus than the learning objectives found in Feisel and Rosa [1], these principles can be used in conjunction with such objectives. Note that most of these principles fall into the affective knowledge domain, dealing with attitudes and behaviors we aim to foster.

Paying close attention to the behaviors occurring in the lab experiments, both intended and unintended, affords one the opportunity to build a more coherent framework of the phenomena in question. If a lab involves disassembly, then paying close attention to how things are put together and taking careful notes is an important skill to have. In addition, the instructor plays an important role in focusing attention on the significant underlying assumptions at hand. For example, if an experiment is dealing with digital circuits, the instructor should explicitly state square wave voltage values represent logic 0s and 1s, and will only remain square if the signal lead lengths are relatively short, otherwise long lead lengths will introduce capacitance which in turn compromises the voltage levels and thus can potentially turn a logic 1 into a logic 0 or vice versa.

Curiosity leads to questions, which lead to hypotheses that can be tested by experiment and whose results can provide deeper knowledge. Following one's own curiosity is likely to be more memorable than following the path of another's curiosity as codified in the written procedure of a given lab. Again, the instructor can help facilitate this curiosity by directing it towards the phenomena being studied or related ones and by helping the student define the procedure needed to answer such questions. By humility, we mean having a constant awareness that you may be mistaken in a hypothesis, and must always be ready to check and re-check assumptions, repeat measurements, etc.

Quality refers to the fact that there may be more than one way to accomplish a task, design an object, etc., but that some will exhibit higher quality than others in the form of greater efficiency, simplicity in design, robustness, etc. Gumption is defined in *Webster's New World Dictionary* (3rd edition, 1988) as (1) shrewdness in practical matters; common sense (2) courage and initiative, enterprise and boldness. We want to bring out whatever common sense students bring to a lab that can be utilized toward learning. We want students to face the lab with "courage and initiative, enterprise and boldness". At first, this may be challenging for some, but by having instructors and some students model this at each opportunity, it can be engendered in more and more students over time.

The robustness we mean is in terms of understanding. Suppose a student assembles a circuit and understands it well. If we intentionally "break" the circuit or otherwise alter it, can the student predict what will happen? Can they return it to its original behavior, even if some of its original components have been taken away, replaced by other different ones? The problem-based principle addresses the fact that much of the standard mode of education starts by providing you with the element (e.g. capacitor) and its properties. Skepticism involves challenging or verifying the suppositions, and if there is an inconsistency between theory and practice, then perform additional investigation to resolve the inconsistency. Many times new discoveries are made because the experimenter is skeptical of the given theory. Problem-based means start with a problem that needs to be solved. For example, if an oscillation is too fast, what element can slow it down? The problem is relevant so we become interested.

Labs in Mathematics Courses

The type of lab we envision can be run not only in science and engineering courses, but also in some mathematics courses. Applications frequently arise in many math courses. Sometimes these are mentioned in the textbook and lectures, occasionally a demonstration of one may occur. But to deepen student learning and retention of mathematical concepts, we propose that hands-on labs be introduced in some mathematics courses. This effort makes the mathematics more interdisciplinary and makes student learning more relevant through meaningful engineering applications. As described above, the intention would be for students to devise these labs and make them relevant to themselves. For example, Newton’s Law of Cooling is often covered in Differential Equations. This could become a lab in which students bring their own heated or chilled item to class. They would come up with the experimental procedure. Having just learned the theory, they would also proceed to solve the resulting differential equation and compare predictions from the solution with observation. As an extension, we could look at situations in which the law starts to break down. What were its assumptions and what leads to violation of them? Again, students could determine the procedure to answer these questions with help from instructors. Other possible lab examples in math courses include sound synthesis using basic trigonometry identities (pre-calculus); volume, surface area and/or work calculations (Calculus II); RLC circuits (differential equations); logic circuits (discrete mathematics), and more. We would expect these labs to not only deepen the learning of the material at hand, but to also strengthen students’ capacities to take charge of their own learning.

Conclusion

This paper considered the problem of shallow learning in students in courses in the physical sciences and engineering. This shallow learning manifests itself in difficulties applying theory to reality and inattention to, or lack of awareness of important assumptions. What is seemingly obvious to a practical engineer or scientist, may be profound to the uninitiated. To address this problem, we offered a new approach to lab courses emphasizing relevancy to the student and student participation in devising the lab. Because these key elements along with other guiding principles we offered make the learning experience more meaningful, they increase the likelihood of deep and lasting learning in the student.

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