The History and Condition of Introductory Physics Teaching Laboratories

Capstone Project

Matt Guthrie

Abstract

Experiment in the laboratory has been a method of education for physics and other science disciplines since at least 1820. The effectiveness of this instructional method has seemingly been contested for just as long as its existence. This paper will review the motivation of physicists to include experiment as a method of instruction, its current state as a viable educational method, and possibilities for improving instruction in the laboratory.

Physics is an experimental science

Physics is the description of nature using general, fundamental laws. It is almost unanimously agreed upon that physics is an experimental science,[1, p. viii][2, p. 2][3, p. 300] a google search for the string "physics is an experimental science" returns about 276,000 results.[4] Physics is generally seen as having two main branches: theory and experiment. These branches build off one another; without experiments to test and inspire theories, physics would still be stuck in its state as it was in the time of the ancient Greeks, more akin to a philosophy than a science.

Research on the way students learn physics is a growing area of interest in the physics community.[5] Ideally, more effective teaching yields students who not only retain more information they're expected to know, but understand the material in a more thorough manner. For example, students often have preconceived ideas about motion, more in agreeance with Aristotle than Newton.[6, p. 2] More effective instruction can remove these misconceptions and advance understanding to further topics. One method of education used ubiquitously throughout physics is in the laboratory, where students experiment on real systems to further their understanding of the physical world.

When materials and budget allow, the American Association of Physics Teachers recommends that every introductory physics course includes a laboratory portion.[7, p. 5] Physicists seem to have some innate feeling that physics instruction should include some laboratory experience.[8, p. 278] Through some collection of common ideals (something quite rare in the community), physics instructors prefer to supplement lecture with some experimentation on real physical systems, not theoretical idealizations. It can be easy to submit to this intuition, but a brief history of some of the first experiments ever conducted could provide some insight into *why* physicists feel so strongly about laboratory exercises. Additionally, looking at what a laboratory curriculum entails, and the effectiveness of current laboratory implementations can reveal how student learning can be improved.

Sizing Up The World

We will first investigate a physical system familiar to every person that has ever lived: the earth. It is common for people to wonder just how large the world is,[9] and with the advancement of science since humanity's origins the answer is not difficult to find in the modern age. However, it is interesting to delve into the history of the search for the answer to this curiosity. As early as 6th century B.C., Hellenistic astronomy had predicted that the earth is spherical (along with the idea of heliocentrism),[10] but other than this guess little was postulated about the planet. We know now that it is nearly spherical with a diameter of approximately $12,756\ km$[11]. Calculations using Newtonian physics and observation from space allow us to calculate properties such as volume and density of the planet, but without these tools how would one estimate the size of the earth? The calculation, to a surprising degree of accuracy, is possible with a very simple experimental setup.

Around the year 240 B.C. in Hellenistic Egypt, Eratosthenes performed what is likely the first ever scientific experiment. At this time, the Greeks are known to have had a good understanding of geometry,[12, Ch. 6] but little other math or science was developed at the time.[13, Ch. 2] Eratosthenes, a well respected scholar and librarian of the Great Library at Alexandria,[14, p. 23] set out to calculate the circumference of Earth.

It is important to realize that in this time, measuring tools longer than about a foot were difficult to come by. Long distances were estimated using the amount of time it took camel caravans to traverse from one point to another. There was no standard unit of distance other than the poorly-defined "stadium," of which there were many definitions, and angles were measured in fractions of a circle. Two of the common definitions of the stadium are equivalent to 157.2 meters (Pliny's stadium),[15, p. 60] and approximately 185 meters (the Attican stadium).

On the summer solstice, deep wells in Syene are illuminated by the Sun. At the same time in Alexandria, shadows are cast from a certain tower (we are not quite sure which, but that really isn't important). Eratosthenes used the average travel time of camel caravans to calculate the distance between Syene and Alexandria, approximately 5000 stadia. Eratosthenes measured the height of the tower and length of the tower's shadow. A diagram showing the geometry involved in this calculation is shown in Figure 1.

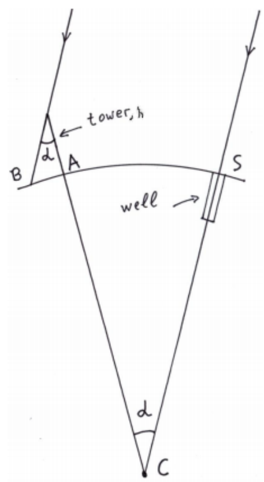

Figure 1: *A diagram of Eratosthenes's experimental setup. A is the location of Alexandria and S is the location of Syene. The angle between the two locations with respect to C, the center of Earth, is* α.[16]

Using the geometry of the figure, $\alpha = \arctan(AB/h)$, where AB is the length of the shadow and h is the height of the tower. He calculated $AB/h \approx 0.14$, thus $\alpha \approx 1/50$ of a circle. Eratosthenes assumed that the Sun is far enough away that its rays are parallel and that at Syene, rays from the Sun are in line with the center of the Earth. Using the Greeks' beloved geometrical relationships, α is the angle between Alexandria and Syene. With $AS = 5000$ stadia, $AS/\alpha = C$, the circumference of the Earth. Eratosthenes's final result for the circumference of Earth was $2.52 \cdot 10^5$ stadia, and using different definitions of the stadium, this could be approximately $3.97 \cdot 10^7$ m (Pliny's stadium) or $4.66 \cdot 10^7$ m (Attican stadium). The currently accepted polar circumference is $4.0008 \cdot 10^7$ m,[17] a percent difference of approximately 0.8% (Pliny's) or 16.5% (Attican). This is an incredibly accurate result considering his setup! This experiment by Eratosthenes is important because it provides a place for scientists to start developing the field. Eratosthenes showed that mathematics can calculate properties of natural systems.

Aristotle to Galileo to Gravitation

Galileo's famous experiment wherein he dropped objects of different masses[1] from the top of the Tower of Pisa and observed them to drop at the same rate, as well as hit the ground at the same time, is commonly considered when people are asked to describe a seminal physics experiment. Until Galileo's time, the accepted model describing the motion of objects was what we now call Aristotelian dynamics. A simple model of Aristotelian dynamics describing the position s of an object in time t can be stated using the equation

$$\frac{\mathrm{d}s}{\mathrm{d}t} = -\gamma s, \tag{1}$$

with $s > 0$ and γ some constant. This could describe how moving bodies come to rest, their natural state.[19, p. 113] The solution to this differential equation is given by

$$s(t) = s_0 \mathrm{e}^{-\gamma t}. \tag{2}$$

Aristotelians taught that falling bodies pick up speed at a rate proportional to the distance they fall, which translates to the differential equation

$$\frac{\mathrm{d}s}{\mathrm{d}t} = ks. \tag{3}$$

The constant k can be made proportional to the weight of the body, an idea consistent with another property of Aristotelian dynamics. This equation's solution is given by

$$s(t) = s_0 \mathrm{e}^{kt}. \tag{4}$$

[1] traditionally thought to be cannon balls[18]

Galileo performed an experiment to test Aristotle's theories and found that the speed $\frac{\mathrm{d}s}{\mathrm{d}t}$ is actually proportional to time.[20][21] He also showed that speed could not possibly be proportional to distance, since with the condition that $s_0 = 0$, s would remain zero even as time increases. These equations suggest that Aristotelian laws of dynamics can be made mathematically sophisticated as Newtonian laws, yet they do not correctly describe nature. The common acceptance of Aristotle's theories was struck down by Galileo's experiment, which explicitly showed that Aristotle's theories were incorrect. This provides a beautiful example for why experimentation is necessary; experimentation allows us sort out the good theories from the bad. Had Galileo not performed his experiment, Aristotelian dynamics would still have been the accepted description of falling bodies. Galileo's equations made way for Newton's discovery of calculus which states that an object's position is related to its initial velocity v_0 and acceleration a by

$$s(t) = s_0 + v_0 t + \frac{1}{2} a t^2, \tag{5}$$

a far cry from the exponential relationships shown in Aristotelian dynamics. Laboratory courses can be useful for the purpose of helping students students to appreciate experimentation, and sorting out good theories from the bad.

Currently, the most generally accepted theory that describes falling bodies is Newtonian mechanics, a special case of general relativity where the velocities involved are small compared to the speed of light. A consequence of the theory of general relativity is that inertial mass is equivalent to gravitational mass, the result that all matter falls at the same rate at corresponding positions in the same gravitational field (and in the absence of other forces). This is formally referred to as the Weak Equivalence Principle, an assertion that Galileo showed to be true in his famous experiment.

Even in our modern age, scientists are performing experiments to test the Weak Equivalence Principle. These can be as rudimentary as constructing sensitive torsion balances[22], or as advanced as designing satellite-based experiments[23]. A simple test of the weak equivalence principle was famously performed by astronaut David Scott[2] on the Moon, dropping a feather and a hammer at the same time and, because of the Moon's lack of a substantial atmosphere, observing them to fall at the same rate.[24] This shows that there is always room for experiment to be more precise.

Experimentation

The general trend of experimentation throughout history can be seen from a Developmentalist point of view: experiments are simple to begin with because more complex experiments test ideas and theories which are not possible to test using simpler experiments. Experiments are known to expand our understanding of nature. This can be explained using Eratosthenes's simple experimental setup, which consisted of little more than a long stick to cast a shadow and a deep well. With Galileo's experiment, the setup was a bit more advanced, requiring a tower and cannon balls. Isaac Newton advanced humanity's understanding of mechanics even further through observations of celestial movement, inventing a new type of telescope in the process.[25, p. 67] Looking even closer to the modern age, with David Scott's experiment, reliable space travel had to be developed. Experiment and technology form a symbiotic circle, simultaneously feeding one another.

Galileo's experiment was part of what some historians call the "scientific revolution." Instead of scientists being more akin to philosophers, scientists involved in this revolution performed experiments, discovered scientific facts to describe nature, and advanced theories to describe scientific processes. Sir Francis Bacon, a scientist during the revolution, even described science as the collection of facts.[26, p. x] This revolution was the spark that ignited many experiments, experimenters, and experimental methods throughout history. For example, what we now teach as the "scientific method"[27] stems from a scientist near the beginning of the revolution called Roger Bacon.[3] Roger Bacon is commonly cited as marking the origin of the scientific method,[28] the method by which instructors often wish their students to perform

[2]Scott was the seventh person to walk on the moon and the first to drive the lunar rover, and flew three NASA missions: Gemini 8, Apollo 9, and Apollo 15. His test of weak equivalence was performed during the Apollo 15 mission.

[3]The exact date for the beginning of the scientific revolution is poorly defined, but Roger Bacon's role in planting the seeds for the scientific revolution is incontrovertible.

experiments.

Experimentation as a method of teaching

With this in mind, we now know that experimentation is important for the advancement of scientific discovery. Education including laboratory instruction has a history traceable at least as far back as Justus Von Liebig's lab in 1820.[29, p. 699] Prior to this, education was purely in the form of lecture. Liebig's laboratory bears little resemblance to a modern introductory teaching laboratory, and is more like what a modern graduate student would experience. Liebig, a German chemist, rejected the accepted methods of teaching chemistry and instead utilized experimentation to teach his students. His methods consisted of giving students ambiguously marked bottles and asked them to identify the contents of the bottles. The students had nothing more than an introductory qualitative analysis textbook to identify the substances and on average the students took approximately a year to complete the exercises to Liebig's satisfaction. As the methods advanced, Liebig's collection of bottles grew to over a hundred.[30, p. 4] Liebig's methods are not foreign to modern instruction, where some classes employ practical laboratories for the purposes of assessment.

Charles Eliot, a professor of mineralogy at MIT, and later a president of Harvard, wrote a mineralogy textbook in 1867 which became a standard work in his field. Incorporated in his textbook are experiments which could be performed either as demonstrations or as laboratory experiments.[29, p. 699] This shows the beginnings of a controversy most prevalent in the 1920s and 1930s between those advocating the laboratory as a method of teaching and those who supported demonstrations in lieu of students performing experiments.[29, p. 699] This controversy is still active today (though much less pronounced).[4] The experimental and demonstration-based methods are quite different in their purpose. Demonstrations can

[4] The contention is very similar to that seen between the Mental Disciplinarians and Humanists of the early 1900s!

clarify a principle but rarely permit in-depth details to be discussed. They also allow for more dangerous principles to be investigated.[5] Experiments enable a more hands-on approach, and allows students to gain practice in actually performing scientific experiments. On the other hand, there is also a higher probability that some students will outpace others, creating a more difficult classroom dynamic for the instructor.

An issue with the implementation of experimentation is the shoddy definition of some main ideas in laboratory instruction, such as *school laboratory* or *lab* and *practical*, which are used without being precisely defined.[31, p. 105] The word "experiment" can mean many things in different contexts, such as investigations or projects that are pursued for several weeks. "Experiment" can also refer to experiences lasting 20 minutes or less.[31, p.106] This can be discouraging to students who are easily confused by nomenclature, such as some international students who know English as a second or third language. Additionally, laboratory activities can incorporate a high level of instrumentation, and at other times the use of any instrumentation has been meticulously avoided.[31, p. 106] Such a poorly defined structure is difficult for students to work around.

McDermott and Shaffer offer a highly structured but interestingly free-form attempt at laboratory instruction with their "learning by doing" Physics by Inquiry curriculum. Physics by Inquiry forgoes all lecturing and uses experiment to teach all material, much like Liebig. McDermott and Shaffer provide an explanation of the reasoning behind their curriculum and details on its development:[32]

> Through in-depth study of simple physical systems and their interactions, students gain direct experience with the process of science. Starting from their own observations, students develop basic physical concepts, use and interpret different forms of scientific representations, and construct explanatory models with predictive capability. All the modules have been explicitly designed to develop scientific reasoning skills and to provide practice in relating scientific concepts, representations, and models to real world phenomena.

Kenneth Tobin's explanation of a "learning by doing" method concluded with his statement that labo-

[5] Discharging a fully-charged $1000\,F$ capacitor is visually impressive and the physics for strong electric fields are rarely investigated in introductory classes, so the demonstration is useful. The demonstration is also quite dangerous if the proper precautions are not taken.

ratory experiments are a way to learn with understanding and at the same time students engage in a process of constructing knowledge by doing science.[33, p. 403] His explanation suggests that meaningful learning is possible in the laboratory if students are given opportunities to manipulate equipment and materials in order to be able to construct their knowledge of phenomena and related scientific concepts. Very much in the same vein as John Dewey, Tobin appeals to the rationalization that the experience is sufficient justification for teaching laboratories. Dewey's theories that experience leads directly to education state that the experience of performing an experiment (with proper guidance) is a sufficient impetus for learning the physics behind the experiment. There are certainly some physicists who would agree.

Goals of Laboratory Instruction

Having a defined set of goals can provide stepping stones for instructors and students to follow throughout the progression of the teaching and learning process. This is, in part, taking example from Ralph Tyler, who stated that we should be "devoting much time to the setting up and formulation of objectives, because they are the most critical criteria for guiding all the other activities of the curriculum-maker."[34, p. 62] This is also in accordance with a Social Efficiency standpoint, which would state that education should not take place until a set of objectives has been chosen.[35, p. 86] To this end, a review of some goals for laboratory education from various institutions can be insightful. Additionally, John Dewey should be kept in mind while considering these goals, as one of his central tenants for education depends on students and their experiences. In this case that could mean the entire experience of the laboratory or simply the experiments themselves, something for the instructor to decide for the students as part of the mentoring process.

The American Association of Physics Teachers defines the following goals for an introductory teaching laboratory:[7]

> I. -The Art of Experimentation: The introductory laboratory should engage each student in significant experiences with experimental processes, including some experience designing investigation.

II.- Experimental and Analytical Skills: The laboratory should help the student develop a broad array of basic skills and tools of experimental physics and data analysis.

III.- Conceptual Learning: The laboratory should help students master basic physics concepts.

IV.- Understanding the Basis of Knowledge in Physics: The laboratory should help students understand the role of direct observation in physics and to distinguish between inferences based on theory and the outcomes of experiments.

V.- Developing Collaborative Learning Skills: The laboratory should help students develop collaborative learning skills that are vital to success in many lifelong endeavors.

These goals resemble a constructivist progression. Encouraging collaboration, experience in exploring scientific concepts, and experimentation, they exemplify qualities common to science curriculum. This is likely a result of educators developing their curriculum on the basis of personal experiences.[36, p. 32] From a constructivist perspective, building on these experiences should help students understand the underlying scientific principles. The recommendation that students work in groups throughout their laboratory exercises is common because of a lack of space for individual work, but also because working in groups increases output quality and overall morale.[37] One useful investigation might be to identify the effects of randomly grouping students throughout the progression of the laboratory course or require them to work in the same group for the term. There are advantages and disadvantages for either grouping method (from personal observation). Students can become complacent in their groups and also can develop more advanced collaboration techniques.

Arnold Arons, a former president of the AAPT, laid out the following guidelines for laboratory instruction in his 1993 article for *The Physics Teacher*:[8, p. 278]

(1) to verify or confirm laws, relations, or regularities asserted in text, class, or lecture;

(2) to have some experience with actual physical phenomena;

(3) to have the experience of, and develop some skill in, handling instruments and making scientific measurements;

(4) to have some experience of planning and doing experiments and thus encountering some of the "processes of science";

(5) to learn something about minimizing error and about the treatment and interpretation of experimental data.

Arons's goals are similar to that of the AAPT, although he replaces conceptual learning with verifying or confirming laws. Confirming laws is objectively in line with a Social Efficiency standpoint. Arons also includes a crucial addition: that of considering errors in the experiment.

In the common tongue, the word "error" usually refers to some kind of mistake. Within the laboratory, "error" has a specific definition, and mistakes are a small part of laboratory error. Error (or uncertainty) is inherent in the performance of an experiment.[38, p. 1] In many experiments, students are asked to answer questions or perform calculations related to a specific error situation, usually one that is well demonstrated in that particular experiment. For example, a student is asked to use a pendulum and stopwatch to find g, the acceleration due to gravity close to the surface of Earth, and calculates $g = 11.5\ m/s^2$, while g is usually accepted as $9.8\ m/s^2$. The student has probably not shown that the equations which lead to $g = 9.8\ m/s^2$ are wrong. An error analysis will likely show that $11.5\ m/s^2$ is consistent with the accepted value of g when experimental error is taken into account.[38, p. 1-2] The analysis of the accuracy and uncertainty of measurements and inferences, commonly termed "error analysis," is essential to interpreting all experiments, especially those designed to test or validate a theory. Lecture courses concern only the established facts of physics, and these issues usually only arise in laboratory courses as a result.

Many introductory laboratories forego formal error analysis because of its mathematical complexity, whereas Arons includes it in his guidelines. This shows an interesting and quite drastic change from other introductory laboratories, usually reserved for more advanced laboratory courses.

Guidelines in use for Michigan Technological University's introductory physics laboratories follow a similar structure to those from the AAPT:[39]

1. See examples of and gain insight into basic physics concepts.
2. Use basic physics concepts to develop critical thinking, problem solving, and decision making skills.
3. Develop specific skills, competencies, and points of view needed by professionals in the sciences including measurement and data analysis.

4. Gain skill in discussing and writing about observations, inferences, and conclusions.
5. Learn to work collaboratively.

These guidelines are more focused on developing skills, such as observation, discussion, and collaboration, for the student's future than those outlined by the AAPT. Emphasizing communication as a goal is not explicitly defined in the AAPT guidelines. This quality is similar to another set of guidelines used for introductory physics laboratories at the University of Rochester, a private university located in Rochester, New York. These guidelines exhibit a more verbose set of goals for an introductory laboratory:[40]

> 1. To provide an experimental foundation for the theoretical concepts introduced in the lectures. It is important that students have an opportunity to verify some of the ideas for themselves.
>
> 2. To familiarize students with experimental apparatus, the scientific method, and methods of data analysis so that they will have some idea of the inductive process by which the ideas were originated. To teach how to make careful experimental observations and how to think about and draw conclusions from such data.
>
> 3. To introduce the methods used for estimating and dealing with experimental uncertainties, including simple ideas in probability theory and the distinctions between random (statistical) and systematic "errors." This is essential in understanding what valid conclusions can be deduced from experimental data and that, properly obtained, these conclusions are valid, notwithstanding the uncertainty of the data.
>
> 4. To learn how to write a technical report which communicates scientific information in a clear and concise manner.
>
> 5. To introduce new concepts and techniques which have a wide application in experimental science, but have not been introduced in the standard courses. These may require that the student consult additional textbooks.

These guidelines provide an explanation for their inclusion in the curriculum. They also include the process of error analysis and the act of communication of results. Collaboration is downplayed in favor of more advanced topics. All of these sets of guidelines have common features, emphasizing experience in performing experiments, experience in real systems (not idealizations), learning physics through experiment (learning to think like a physicist), and learning why experiments are important. Experiments deal with nature as it is, not as we would like it to be. The mathematical laws of physics are exact, with the qualification that they are idealizations of real experiments and only provide inferences based on initial conditions or inputs having a finite accuracy. Establishing that these laws properly describe nature requires showing that the inferences are as accurate as possible, given the accuracy of the input.

To contrast these seemingly well thought-out goals, the goals of PHY 101L, an introductory mechanics laboratory for students majoring in physics at The University of Texas, are shown:[41]

1. To illustrate the principles of [physics] by applying them to natural systems.

2. To quantify experimental accuracy as an essential part of experimentation.

These goals seem to have skipped some steps. There is an assumption that people have gone through the material in class and understood that material completely. Furthermore, there is another assumption that students can apply that knowledge in a laboratory setting. Experimental physics difficult and requires good technique; students are not necessarily equipped to surmount these obstacles at the beginning of their first laboratory course. These goals do not include any consideration of the students involved in the process (the way they're supposed to be learning, the purposes for performing experiments, or specific experiences), and seem to be more suited towards an advanced laboratory instead of an introductory laboratory, where the students should have already learned from the omitted goals in earlier courses. The students in PHY 101L are often taking their first laboratory class and are completely bewildered by many of the experiments. Properly prepared goals can guide experiments, students, and instructors through the laboratory experience. Just as the Social Efficiency educators state, the development of a set of goals for an introductory laboratory is one of the most important considerations for the design of the course. The guidelines should be a starting point, not an afterthought.[7]

Laboratory effectiveness

Although teaching laboratories have been in use for hundreds of years, intense controversy has developed at times regarding the usefulness and effectiveness of introductory laboratories "as far as one cares to go back in the literature."[8, p. 278] Hofstein and Lunetta have published two review articles, twenty years apart, which examine the state of laboratory instruction.[42][36] These authors clearly set out to affirm the necessity of introductory teaching laboratories, and even their first review article struggles to find a justification for teaching laboratories. Hofstein and Lunetta show that, at the time, the teaching laboratory had little measurable effect on the educational achievement of students.[42][29, p. 699]

Addressing this disturbing finding is of the utmost importance. Most arguably, the hinge pin of laboratory instruction is guidance. As Pickering says, "few things are as utterly pointless as measuring something when you are not quite sure what you are measuring, or why."[29, p. 700] Some students can succeed with minimal instructor support, but a vast majority will simply run through the procedure without considering what they are doing or why. One problem can be attributed to the experiments themselves. Beginning laboratories often focus on the act of measuring quantities and do not lead students to consider the motivation behind these measurements.[29, p. 700] Orienting experiments away from pure measurement and computation may relieve some tension caused by constant measurement.

Alfred Whitehead provides an interesting perspective on not just laboratory instruction, but instruction in general. He warns of teaching "inert ideas," or "ideas that are merely received into the mind without being utilised."[43] This is especially important to avoid in the laboratory, where inert ideas can not only hold back one student, but an entire group. It is difficult to imagine such a large waste of time and resources as measuring something without knowing why the measurement is being taken, what is being measured, or even *how* the measurement was performed.[29, p.700] Yet, this is how most laboratory manuals are written. These materials assume that scientific insight will develop as a result of the experience.[8, p. 279] Unstructured experiments can be ineffective, but Arons warns that too much structure can be just as demoralizing for students and will "generate little in the way of concept development or physical understanding"[8, p. 279] He explains that most students do not make significant progress without help or guidance from an instructor.[8, p. 279] Just like in Dewey's method, laboratory instruction requires more instructor involvement than many instructors are ready to provide. The instructor should be able to give Socratic guidance without revealing too much about the situation under examination.[8, p. 279] Arons puts it quite elegantly: "The 'Why do we believe...?' question should be posed at the start and should be the principal goal of the investigation."[8, p. 280] After all, for the Dewey curriculum to be effective, student interest must motivate the experience.[44, p. 54]

Is the laboratory experience necessary?

Historically, physicists would unanimously say that laboratory experience is necessary to build a foundation of physical understanding and that "laboratory training is also frequently used to develop skills necessary for more advanced study or research."[45, p. 1] For students not destined for more advanced study or research, the conclusion becomes less definitive. As demonstrated by the Physics by Inquiry curriculum, it is possible to teach a completely self-contained laboratory experience.[46]

One could argue that the experience is the goal of introductory laboratories, that they should learn how new sciences are discovered through experiment. It is unfortunate that this experience is in many instances curtailed by the assessment process. Often, students new to the experience of being in a laboratory are effectively punished for not having the same experiences as their more advanced peers. This is avoidable using proper teaching methods but much more difficult in the context of a laboratory. If the laboratory experience is partially about discovering scientific principles, students must not be punished for being inexperienced at the onset of a lesson.[8, p. 281] Students should be assessed based on their improvement throughout the course. Pitting students against one another in a laboratory does not lead to constructive assessment, especially when considering the goal of developing collaborative techniques.

If the laboratory experience is to be preserved,[6] instructors must learn from the previous research. Most importantly, the laboratory must not be utilized without a purpose. It is the purpose that drives us

[6] As opposed to being lost to budget cutbacks or because of poor student reviews.

through the experiments and experiences of a laboratory setting. This is as true in research as it is for an introductory laboratory.

Future trends

Pickering provides three options for the future of the laboratory as a catalyst for instruction.[29, p. 699-700]

(1) *We can go on with labs as they are.*

(2) *We can drop labs entirely, except for the training of future scientists.*

(3) *We can try to improve.*

Students performing experiments without rhyme or reason does not have a positive effect on learning, but it does not have a measurable negative effect either.[29, p. 700] Continuing with traditional lab experiments for the sake of tradition, and putting physicists' innate feelings at ease, is not a financially sound justification. For the sake of this argument, financial consideration is important. Laboratory equipment and instructor time is costly, and often school administration is looking for ways to reduce unnecessary spending. Unfortunately this can be demoralizing to physicist instructors who feel that students need some kind of laboratory experience. The remaining option is that of improving the experience for all students, making sure they are using their time wisely and effectively. A short perspective piece by Hofstein and Mamlok-Naaman shows that "new standards intended to shape and rejuvenate science education are emerging."[31, p. 105] The problems that plague laboratory instruction are not insurmountable, with research in the development of curriculum science educators can improve the quality of laboratory education.[45, p. 2]

It could be that we are not asking the right questions in trying to analyze the outcome of these laboratory courses. When trying to explain the sufficience of laboratory experiences, Blosser explains that we should not be asking "What is the laboratory better than?," and instead ask "For what purposes should the laboratory be used, under what conditions, and with what students?".[45, p. 2] These questions will reveal more effective results, rather than simply stating that outcomes are not as high as expected.[45, p. 2]

Students often complain that introductory laboratories consist of "busywork."[47, p. 195] In response, there have been efforts to use examples from everyday life and analyze using theory from a lecture course. Furthermore, in-class examples and homework problems utilizing situations from movies[48] or history are common in lecture courses. A dedicated curriculum wherein students design an experiment to demonstrate a scene from a movie has not yet been developed. Some of these model situations can be simply translated into a physical experiment, such as a space station shown in Stanley Kubrick's *2001: A Space Odyssey*. The film contains a prevalent theme of rotation, everything is rotating, including space stations, one of which is shown in Figure 2.

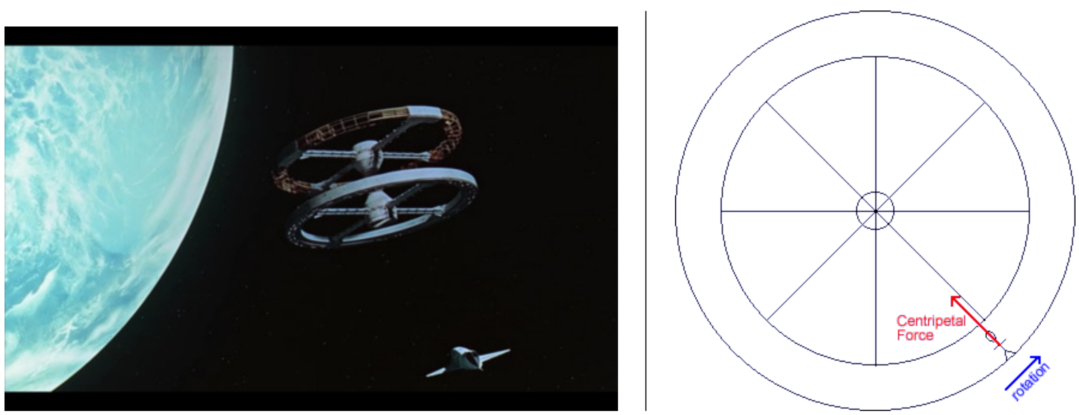

Figure 2: *The rotating Space Station V in 2001: A Space Odyssey, and a diagram showing the forces involved.*[49][50]

A method of simulating a gravitational force in space can be utilized through centripetal motion. Constructing an experiment to prove the required angular speed for proper simulation of g is an example of the kind of experiment possible. Having students choose a film they are interested in and designing an experiment to illustrate a physical principle shown, such as the infamous bus jump scene from *Speed*, shown in Figure 3, could help hold the interest of students.

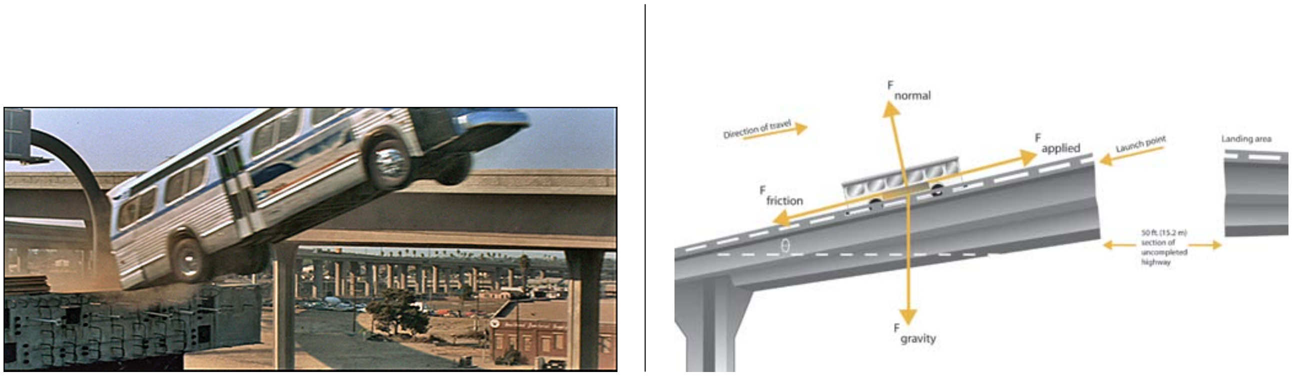

Figure 3: *The iconic scene from Speed, where a bus jumps approximately* 50 *feet over an uncompleted section of highway, and a diagram showing the forces involved.*[51][52]

To test this situation, a scale model could be built that demonstrates the physics involved in the jump. This would be investigating a real physical system, would give the student experience designing an experiment, and could easily incorporate an error analysis. All of the guidelines from the AAPT (and more) are satisfied with this experiment. Having students design experiments such as these could help them see that physical phenomena are not unique to a lecture course and are not abstract concepts. The students may even complain less about having to waste their time with "busywork."

Another substitution for laboratory experience could be to relinquish a teaching laboratory in favor of a proper research laboratory, such as in The University of Texas's Freshman Research Initiative (FRI).[53] The FRI includes integration in lecture courses and laboratory work in actual research labs. The collaboration goal is met since students progress through the program in cohorts of about 30 students. The University of Texas's College of Natural Sciences states that "Students emerging from FRI have experience with experimental techniques, lab work, and a deep understanding of the scientific process and sometimes publications."[53] This indicates that students have the possibility of gaining the experience of a professional researcher much earlier than most of their peers, while still experiencing a laboratory science.

Conclusion

A teaching laboratory is not effective unless instructors can properly convey the purpose for performing the accompanying experiments. It is not enough for a teacher to know the material; the manner in which it is presented is just as important in the teaching process. For a laboratory experience, this requires teacher involvement and student interest. Rarely will a student succeed in such a free form environment as a laboratory without some guidance. Pickering's optimism about the laboratory experience is infectious: "The potential for laboratory is enormous. The laboratory exercise at its best is the fundamental intellectual task of extracting truth from ambiguity, signal from noise. It is a lesson in comparing and evaluating evidence, a central part of intellectual maturity. Unfortunately, many laboratory programs are not taught in a way that brings this out."[29, p. 700]

To continue with laboratory as a viable method of instruction, it must be continually updated and improved. McDermott and Shaffer's Physics by Inquiry is a tremendous step in the right direction, although some physicists are undoubtedly wary of substituting a purely laboratory-based course in place of a lecture with a laboratory supplement. There is, of course, a strong motivation for physicists to include laboratories in student education. This is beautifully summarized by Richard Feynman.[54, p. 1-1]

> "The principle of science, the definition almost, is the following: The test of all knowledge is experiment. Experiment is the sole judge of scientific 'truth.' But what is the source of knowledge? Where do the laws that are to be tested come from? Experiment, itself, helps to produce these laws, in the sense that it give us hints. But also needed is imagination to create from these hints the great generalizations - to guess at the wonderful, simple, but very strange pattern beneath them all, and then to experiment to check again whether we made the right guess."

Bibliography

[1] H. Crew. *The elements of physics: for use in high schools*. The Macmillan company, 1901.

[2] K.A. Tsokos. *Physics for the IB Diploma*. IB Diploma. Cambridge University Press, 2010.

[3] E. Khalil. *Dewey, Pragmatism and Economic Methodology*. Routledge INEM Advances in Economic Methodology. Taylor & Francis, 2004.

[4] "physics is an experimental science", April 2014.

[5] John Thompson and Bradley Ambrose. A literary canon in physics education research. `http://units.aps.org/units/fed/newsletters/fall2005/canon.html`, Fall 2005.

[6] I. A. Halloun and D. Hestenes. Common sense concepts about motion. *American Journal of Physics*, 53:1056–1065, November 1985.

[7] Guidelines for two-year college physics programs. `http://www.aapt.org/Resources/upload/TYCGuidelines-PDF.pdf`, 2002.

[8] A. B. Arons. Guiding insight and inquiry in the introductory physics laboratory. *The Physics Teacher*, 31:278–282, May 1993.

[9] Colm Byrne. How big is earth. `http://www.planetsforkids.org/news/how-big-is-earth/`, January 2013.

[10] Who discovered that the earth was round? http://www.ask.com/question/who-discovered-that-the-earth-was-round, April 2014.

[11] What is the diameter of the earth? http://geography.about.com/library/faq/blqzdiameter.htm, April 2014.

[12] J. Gow. *A Short History of Greek Mathematics*. A Short History of Greek Mathematics. Cambridge University Press, 2010.

[13] T. Goldstein. *Dawn of Modern Science: From the Ancient Greeks to the Renaissance*. Da Capo Press, 1995.

[14] K. Trumble and R.M.I. Marshall. *The Library of Alexandria*. Houghton Mifflin Harcourt, 2003.

[15] P. Holland and Wernerian Club. *Pliny's Natural History in Thirty-seven Books*. Number 1-3 in Pliny's Natural History in Thirty-seven Books. Club, 1848.

[16] K.N. Boyadzhiev. Eratosthenes and pliny, greek geometry and roman follies. *ArXiv e-prints*, June 2010.

[17] Tim Sharp. How big is earth? http://www.space.com/17638-how-big-is-earth.html, September 2012.

[18] Ruth Netting. Was galileo wrong? http://science1.nasa.gov/science-news/science-at-nasa/2004/06may_lunarranging/, April 2011.

[19] W.E. Doll. *A post-modern perspective on curriculum*. Teachers College Press, New York, 1993.

[20] Galileo Galilei. *The Discourses and Mathematical Demonstrations Relating to Two New Sciences (Discorsi e dimostrazioni matematiche, intorno due nuove scienze)*. 1638.

[21] Galileo - gravity and acceleration. http://clivemabey.me.uk/SciTech/gravity/galileo.php.

[22] T. A. Wagner, S. Schlamminger, J. H. Gundlach, and E. G. Adelberger. Torsion-balance tests of the weak equivalence principle, 2012.

[23] Microsatellite for the test of the equivalence principle. `http://smsc.cnes.fr/MICROSCOPE/index.htm`, April 2014.

[24] Weak equivalence principle test on the moon. `https://www.youtube.com/watch?v=MJyUDpm9Kvk`, May 2007.

[25] A.R. Hall. *Isaac Newton: Adventurer in Thought.* Cambridge Science Biographies. Cambridge University Press, 1996.

[26] F. Bacon and J.M. Robertson. *The Philosophical Works of Francis Bacon: Reprinted from the Texts and Translations with the Notes and Prefaces of Ellis and Spedding.* Routledge, 1905.

[27] B. Gower. *Scientific Method: A Historical and Philosophical Introduction.* Routledge Advances in Management and. Routledge, 1997.

[28] R. Bacon and J.H. Bridges. *The Opus Majus of Roger Bacon, preface.* Number 1 in Cambridge Library Collection - Physical Sciences. Cambridge University Press, 2010.

[29] Miles Pickering. The teaching laboratory through history. *Journal of Chemical Education*, 70(9):699, 1993.

[30] C. de Waal. *Peirce: A Guide for the Perplexed.* Guides for the Perplexed. Bloomsbury Academic, 2013.

[31] Avi Hofstein and Rachel Mamlok-Naaman. The laboratory in science education: the state of the art. *Chem. Educ. Res. Pract.*, 8:105–107, 2007.

[32] Physics by inquiry. `http://depts.washington.edu/uwpeg/pbi`, April 2014.

[33] Kenneth Tobin. Research on science laboratory activities: In pursuit of better questions and answers to improve learning. *School Science and Mathematics*, 90(5):403–418, 1990.

[34] R.W. Tyler. *Basic Principles of Curriculum and Instruction*. University of Chicago Press, 2010.

[35] M. Schiro. *Curriculum for Better Schools: The Great Ideological Debate*. Educational Technology Publications, 1978.

[36] Avi Hofstein and Vincent N. Lunetta. The laboratory in science education: Foundations for the twenty-first century. *Science Education*, 88(1):28–54, 2004.

[37] Edmond Lau. Why and where is teamwork important? `http://www.forbes.com/sites/quora/2013/01/23/why-and-where-is-teamwork-important/`, January 2013.

[38] Matt Guthrie. Phy 101l - experiments in mechanics - introduction to error analysis. April 2013.

[39] Michael Meyer. Ph1100 policies and procedures. `http://phy.mtu.edu/~mrmeyer/ph1100_policy.pdf`.

[40] Prof. Frank L. H. Wolfs. The purpose of the laboratory. `http://teacher.nsrl.rochester.edu/phy_labs/Purpose/Purpose.html`.

[41] K.W. Gentle. *Physics 101L Laboratory Manual - Experiments in Mechanics*. 2012.

[42] Avi Hofstein and Vincent N. Lunetta. The role of the laboratory in science teaching: Neglected aspects of research. *Review of Educational Research*, 52(2):pp. 201–217, 1982.

[43] A.N. Whitehead. *Aims of Education*. A Free Press paperback. Free Press, 1967.

[44] H.M. Kliebard. *The Struggle for the American Curriculum, 1893-1958*. RoutledgeFalmer, 2004.

[45] Patricia E. Blosser. The role of the laboratory in science teaching. *Research Matters - to the Science Teacher*, (9001), March 1990.

[46] Articles and dissertations motivated by physics by inquiry or related research. https://depts.washington.edu/uwpeg/sites/default/files/files/V5%20-%20TOC.pdf.

[47] James A. Shymansky and John E. Penick. Use of systematic observations to improve college science laboratory instruction. *Science Education*, 63(2):195–203, 1979.

[48] Tom Rogers. Insultingly stupid movie physics. http://www.intuitor.com/moviephysics/.

[49] Stanley Kubrick and Arthur C. Clarke. 2001: A space odyssey, 1968.

[50] JL Stanbrough. Simulating gravity in space. http://www.batesville.k12.in.us/physics/PhyNet/Mechanics/Circular%20Motion/simulating_gravity.htm, February 2008.

[51] Gary J. Wayne. Speed filming locations part 4. http://www.seeing-stars.com/Locations/Speed4.shtml, 2007.

[52] Bob Horton Jeff Marshall and Joyce Austin-Wade. Giving meaning to the numbers. http://www.nsta.org/publications/news/story.aspx?id=53246, January 2007.

[53] Freshman research initiative. http://www.cns.utexas.edu/fri.

[54] R.F. Feynman and R.B. Leighton. *The Feynman Lectures on Physics*.