1-2015

The Introductory Physics Lab as a Consulting Firm

Daniel O. Ludwigsen

122nd ASEE Annual Conference & Exposition
June 14 - 17, 2015
Seattle, WA
Making Value for Society

Paper ID #12634

The Introductory Physics Lab as a Consulting Firm

Dr. Daniel Ludwigsen, Kettering University

Dr. Daniel Ludwigsen pursued research in Musical Acoustics while completing the Ph. D. in Physics from Brigham Young University. After joining Kettering University in support of the acoustics specialty within Applied Physics, Dr. Ludwigsen has broadened his professional interests to include physics education research and instructional design. In addition to an overhaul of the introductory physics laboratories, partially supported by NSF CCLI funding, Dr. Ludwigsen has written two courses at the sophomore/junior level, and coauthored a senior level laboratory in acoustics. He recently served as an AP Reader for the AP Physics exam, and is interested in developing materials to help K-12 teachers with units on sound and waves, and to incorporate crash safety topics into their physics curriculum.

The Introductory Physics Laboratory as a Consulting Firm

Abstract

Many students in our calculus-based introductory physics courses plan to pursue careers in high technology industries. The laboratory curriculum entitled *Mechanics, Inc.* is designed to resemble the typical work environment of an R&D consulting firm. Upon entering, students begin a series of training activities focused on applications of physics topics to situations of interest to ersatz clients. These physics topics are chosen to complement the usual sequence encountered in the classroom. Inspiration for the instructional design of the curriculum comes from Modeling Instruction, a well-known approach disseminated to science teachers in workshops across the country, and from Cognitive Apprenticeship, which is less well known in physics pedagogy but widely used in language instruction and other areas. Students are coached and guided in the development of laboratory skills, application of physics concepts, and in the communication of laboratory work in a formal report. During the training activities, components of that formal laboratory report are added sequentially; the initial emphasis is on readable figures and captions. After several activities that each focus on another section of a conventional report, the final training activity brings all sections together in a full, formal laboratory report. With a few weeks remaining in the course, the students apply what they have learned in training activities to tasks needed by another ersatz client. These present somewhat ambiguous problems that students must first clarify. Their responses to the client's challenges are presented in a formal laboratory report.

The explicit emphasis on communication skills, recognition of impact in a client-consultant relationship, and freedom given to students to develop their own solutions requires very clear, intentional facilitation. Training for instructors is critical to implementation of this instructional design, as indicated in preliminary assessment of initial pilot terms. Surveys of student attitudes toward physics are also being brought into the assessment structure of *Mechanics, Inc.* The overarching goals for this curriculum are to shift the mindset of students taking the introductory physics laboratory toward curiosity, and provide them with the practical tools used by scientists and engineers in a variety of contemporary workplaces.

Purpose

Mechanics, Inc. is a laboratory curriculum written for the first semester of the traditional calculus-based physics sequence, with topics in mechanics. This paper is intended to introduce the structure and pedagogical approach in this curriculum—designed to influence the mindset of students as they begin the pursuit of STEM subjects at the college level.

Background

The laboratory component of introductory science courses has evolved over the last five or six decades. Borrowing taxonomy from chemistry education,[1] the general trend has developed from expository or verification laboratories to inquiry-based laboratories, which can be categorized as either open inquiry or guided inquiry activities. The review by Hofstein and Lunetta[2] provides a snapshot of this evolution toward activities that guide students as they construct their own knowledge of a subject. The American Association of Physics Teachers (AAPT) has produced a policy statement[3] with five goals for introductory physics laboratories, which recognizes the changing and evolving design of these activities that has accompanied a maturing and deeper understanding of student learning. More recently, the AAPT produced recommendations[4] for undergraduate laboratories with specific mention of skills in modeling, communication skills, and, at the center of their suggestions, the construction of knowledge through carefully designed experiences and activities.

In the middle of the last century, with an emphasis on science and engineering driven by the space race, introductory laboratories tended to be expository in style and focused on verifying relationships or concepts in a deductive approach. In this type of laboratory, instructions tend to be direct, the manual often has space to record the data gathered by students as they execute the steps, and the analysis also proceeds according to instructions. Usually, there are post-lab questions for reflection and interpretation of results. On the other hand, inquiry based laboratories tend to use an inductive approach in which students arrive at the general principle by gathering evidence. In an open inquiry activity, the students create the method for gathering data and perhaps even the question to be addressed. The outcome is undetermined by the curricular materials. Activities that employ a guided inquiry style are also inductive, but have a predetermined outcome and the procedure is provided in the manual or by the instructor.

Another area of curricular development aims to incorporate industry-relevant or authentic research situations. Case studies and problem-based learning formats have become popular across STEM disciplines. Concurrently, the methods of facilitating classroom, studio, and laboratory activities have shifted toward a focus on the student. Rather than simply presenting information, the role of the instructor is increasingly that of a guide, coach, or mentor, aiding the student in constructing her own knowledge. We live in a setting of easily accessible information; formal instruction becomes less about access to knowledge, and more about processing of knowledge.

To some degree, the role of the student can be seen as that of an apprentice. Apprenticeship began centuries ago as a long term program of study to learn a craft. Today, an apprenticeship program may start at the secondary school level for vocational training, an example deployed in several European countries. In this country, apprenticeships are offered to introduce young people to cutting edge science and engineering research.[5] However, in this context the term is used to describe the pedagogical approach, used in a shorter time scale more appropriate for a weekly laboratory course.

Multiple styles of apprenticeship pedagogy describe the interaction between master and apprentice. Cognitive Apprenticeship from the field of instructional design[6] fits this project; it has been applied widely in the context of language, reading comprehension, and mathematics.[7] The Collins-Brown model includes several key features:

- Course content *explicitly provides those rules of thumb and heuristic knowledge* that experts use (often without knowing it).
- Course content is provided in *authentic contexts based on real situations* where it would be used.
- Course content and facilitation *supports students' development of skills and knowledge of processes with appropriate scaffolding*, gradually removing it as the learner progresses.
- Course facilitation includes *modeling and explaining* the processes used in thinking through a problem.
- Course facilitation includes *observation, coaching, and one-on-one attention* for students, without interfering in the students' development of their own cognitive skills.
- Course design provides students with opportunities to (i) explore different strategies that may or may not work, and (ii) reflect on their actions and choices, making them explicit. This combination *allows students to develop and refine the mental models of experts*.

Much of this is already captured in physics education, in a movement known as Modeling Instruction.[8] This is a method that aims to correct many of the weaknesses of traditional teaching via lectures and demonstrations: including the fragmentation of knowledge, student passivity, and the persistence of naive beliefs about the physical world. Its objectives include encouraging students to develop, and later deploy, scientific models that describe, predict, and explain physical phenomena. The Modeling Instruction class explores content through discussions shaped by questions, first from the instructor, but later by the students. These questions clarify their models and move away from typical misconceptions, fragmented thinking, and reference to jargon. Students are required to present and justify their conclusions orally, often on a portable whiteboard, explaining the model for the phenomena in question and evaluating the model in comparison with data.

Instructional Design

The Mechanics, Inc. laboratory curriculum is designed to develop gradually students' laboratory skills and improve communication of their work. As students complete a series of Training Activities, they build upon previous lessons and ultimately write a complete formal lab report to communicate their model of a complicated phenomenon. The course culminates in Client Challenges centered on similarly complicated mechanical problems. These activities are designed to build toward course learning objectives that are not unusual for an introductory physics laboratory:

When you complete this course, you should be able to…

1. Collect data with an understanding of uncertainty in measurement and sensor characteristics
2. Graph and analyze data for comparison with theoretical expectation, assessing goodness of fit and/or correlation

3. Explain methods of computer-assisted data analysis (e.g. numerically differentiate and integrate data from graphs)
4. Critically interpret results of analysis
5. Plan and perform an experiment from hypothesis through execution
6. Apply physical concepts of force, energy, and work
7. Communicate the entire lab experience via a formal lab report

The Training Activities are described in more detail in Table 1. Each one explores a topic from physics that would be aligned with the classroom presentation in a typical sequence. Each Training Activity also features a Client Case, some example of the application of the topic to industrial, clinical, or everyday settings. Finally, each Training Activity emphasizes a particular aspect of scientific communication, as well as a specific laboratory skill relevant to the investigation of the topic. The Training Activities are designed for deployment in a two hour session held once per week, except the last one that spans two weeks.

Table 1. Progression of Training Activities

Training Activity	***Physics Topic***	***Client Case***	***Laboratory Skill***	***Communication***
1: *How do we know what we know?*	Position and velocity	Toy Theremin	Sensors, uncertainty, and data acquisition equipment	Support all claims with evidence
2. *How do we tell the story of what we know?*	Position, velocity, and acceleration	Toy Airboat	Data analysis, curve fitting	Effective presentation in graphs and tables
3. *How do we build a better experiment?*	Pendulum motion	Floor slip resistance testing, leg drop test for spasticity, ballistic pendulum	Design of experiment and video analysis	Concise and thorough description of the method of an experiment; clear presentation of results
4. *How do we build a better test?*	Newton’s laws	(Student supplied, based on their experiences)	Experimental agreement and propagation of uncertainty	Method, Results, and Discussion
5. *How do we report lab work?*	Newton’s laws with tension, pulley, string, friction	Specifications for a friction pad based on empirical data	Comparing theory and experiment	Assembling a formal lab report

The regular cycle of activity involved in Training Activities includes a set of Prep Problems due before class, an Explore section interspersed with Checkpoints for discussion, follow up Post Problems that are submitted by the team, and an individual Quiz over the concepts and skills from the Training Activity. When completed successfully, the students arrive prepared with background knowledge and an overview of the laboratory work. They are then guided through questions that can be addressed experimentally, and their understanding of results is aligned in group discussion periodically throughout the session. The students are responsible for producing deliverables as a team, but are also assessed on an individual basis.

The final Training Activity is a pivotal one, as students are guided through the writing of a formal lab report. Up to this point, their weekly deliverables were only portions of that report. Two weeks are used for the final Training Activity, so that significant reflection can be devoted to the model. The Half-Atwood machine is the physical system being tested, consisting of a low-friction cart on a track on the lab bench, connected by a string over a pulley to a freely hanging mass (as shown in Figure 1).

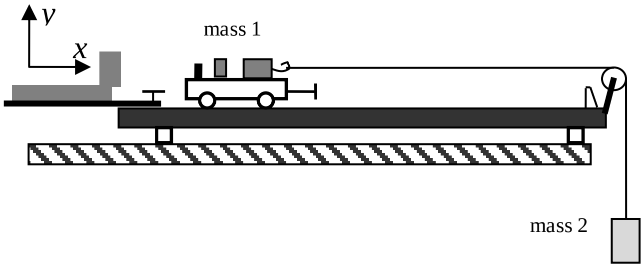

Figure 1. The Half-Atwood machine includes two masses connected by a light string over a light pulley. Gray boxes are sensors.

A motion detector provides position data (shown in Figure 1 at the left end of the track), a force sensor mounted on the cart gives the tension in the string, and acceleration of the cart is found either from the motion detector data, or directly from an accelerometer on the cart. There is a rich set of data available to connect to a theoretical description.

The reflection and iteration built into the students' experience in Training Activity 5 allows them to examine their results and compare with their theoretical model, and refine one or both to better understand the dynamics of this system. For example, students might model the situation using Newton's second law, and ignore rolling friction and air drag. In a particular method of graphical analysis of their acceleration results, a negative intercept can lead them to suspect the impact of friction in the data. Then, if they build that into their model, they can design an experiment to determine a value for the coefficient of rolling friction to more thoroughly quantify and describe the apparatus. Thus the client case is relevant, in which a friction pad can be characterized through careful testing.

Having the final Training Activity as a template for a two-week investigation culminating in a formal report, the students take on Client Challenges. These are developed in partnership with a research laboratory facility on campus, and they further demonstrate how topics from this introductory physics class can be applied to cutting edge research activity. In the present version of Mechanics, Inc., the client is the Crash Safety Center of Kettering University, engaged in testing automotive components to improve occupant safety. The first challenge is concerned with momentum and impulse during a collision, again using the low friction carts on bench-top tracks. Students design a bumper to slow and, ideally, stop the cart at the end of the track. Time history data from a force sensor is used to find impulse, and the students try to design a bumper that minimizes the peak magnitude of the force while maintaining a test protocol that provides a reasonably high impulse for the event. Taking the challenge further, students are tasked with designing a bumper that provides a “pulse” (the plot of acceleration vs. time) that lies within a specified corridor. This is critical in testing for occupant protection in crash safety, and students quickly realize the effect (or non-effect) of design changes in their paper bumpers.

Ongoing refinements to the curriculum have been driven by feedback from both instructors and students. For example, the second challenge is concerned with the question of energy and occupant restraints like seat belts. When a person is traveling with the vehicle at some speed (and thus kinetic energy) and a collision occurs, a seat belt restrains the person to slow down with the vehicle. There is some relative motion of the person in the vehicle frame of reference, but the kinetic energy of the person measured in the lab frame is eventually lost. Where did the energy go? Students explore, on a smaller scale, the force, acceleration, and position data when a low-friction cart collides with various restraints across the track as shown in Figure 2. Unfortunately, students can be confused in this open inquiry format. Students apparently left the lab thinking that an elastic seat belt would be safer than the fibrous webbing used in vehicles, so changes in both the curricular materials and instructor facilitation clarified that Client Challenge.

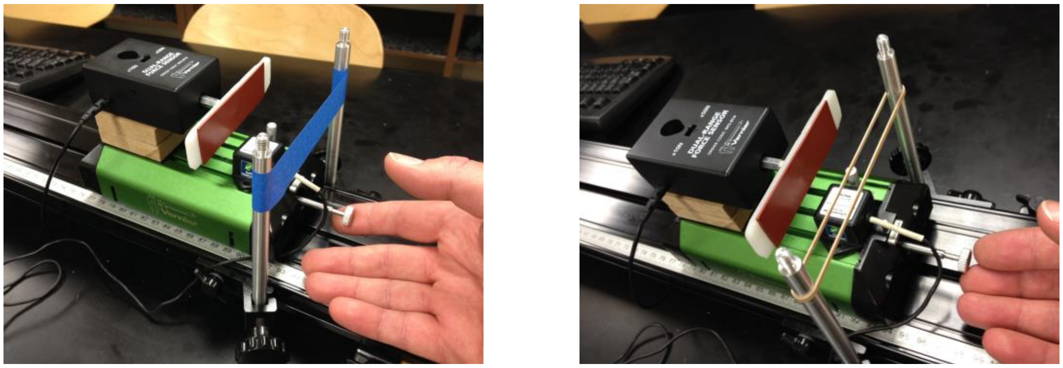

Figure 2. Apparatus for the second Client Challenge, investigating energy loss in collisions. The “restraint” in the setup on the left is blue masking tape; on the right a rubber band is used.

Formative Assessment from Instructors and Students

The curriculum was introduced to Kettering University physics faculty and instructors in a one day workshop. Participants worked through individual Training Activities, and in that context the Modeling Instruction and Cognitive Apprenticeship pedagogical background was motivated. Participants noted that the curricular materials would not succeed without appropriate facilitation techniques.

The initial deployment of Mechanics, Inc. occurred during the Summer academic term in 2014. Three faculty instructors led four sections of lab, with a total of 45 students. The following term, Fall, involved 54 students in four sections led by a returning instructor from Summer and a new instructor.

Instructors were asked to complete an open ended assessment after being reminded of the goals of the curriculum development project. The three questions asked, “What are the strengths of Mechanics, Inc., and why?”, “What are the areas in which Mechanics, Inc. can be improved, and how?” and “What insights did you realize through Mechanics, Inc., and what impact might they have?” The responses collected from instructors during the Summer and Fall terms have been condensed around a few recurrent themes.

Strengths noted by instructors included freedom and flexibility of the inquiry format, especially as students developed the autonomy gradually through the Training Activities. The open-ended problems inspired much greater team interaction and discussion than we had seen using previous laboratory curricula. Checkpoints for class discussion were implemented differently by different instructors, but served as a way to ensure that a room full of diverging teams captured the essential components of the lesson. The Client Challenges encouraged students’ creative problem solving, and allowed them to demonstrate resourcefulness in the process. Also, several faculty commented on the tools incorporated in the Mechanics, Inc. curriculum, including small whiteboards for each team to present their work during discussion. Finally, faculty noted a strength in the curriculum design; it gradually teaches students to compose a complete, formal lab report. Professional scientific communication is an ongoing focus of continuous improvement efforts in this physics department, and so this is of current interest among faculty.

Instructors found that there is room for improvement in the initial deployment during these terms of 2014. One concern was with effective assessment and evaluation of student performance. Instructors were provided with rubrics to evaluate weekly student performance in the Training Activities, and another rubric for evaluating the formal lab reports. Instructors tended to vary in their application of these tools, and some noted difficulty if applied too closely with a section of up to 24 students or eight teams. Another issue that will be addressed in a future version of the curriculum is related to consistency in the scaffolding, or gradual building up of student skills. Tools such as the whiteboards, or video analysis for tracking motion, were introduced early and not reinforced later in the term. Similarly, the Training Activities each introduced an element of a formal report, but a significant fraction of students did not continue to apply that knowledge in subsequent weeks. For example, Training Activity 2 describes features of professional figures and tables, but Training Activity 3 misses the opportunity to remind students of these features as they tabulate data or create a figure to show the results of the experiments they design.

Instructors were generally new to this style of pedagogy in the laboratory, but accepted its premise to keep the focus on students’ development of skills and knowledge. They report insights regarding facilitation, including the importance of some structure (i. e., the Checkpoints) in the context of the open inquiry format. One instructor acknowledged the need to suppress an urge to “jump in and help” while teams worked out their own solutions, while another observed that some teams were frustrated with the coaching approach, and “just wanted me to answer their questions directly and tell them what to do so that they could get done with the lab.” Another insightful instructor noted that at this introductory level, students were very engaged in the work but lacked the habits of mathematical expression of physical relationships. This, of course, is part of the Modeling Instruction and Cognitive Apprenticeship paradigms; these habits must be cultivated through intentional effort over time, and cannot be assumed to be present in the students from the beginning.

As part of the free-response instructor feedback, one of the faculty provided unedited *student* comments. Those relevant to the Mechanics, Inc. curriculum and facilitation are reproduced here, also unedited (including the spelling and other errors).

General Comments:

- The course could use a little bit more instruction on what students are expected to do.

- As a lab, the idea is to make sure the kids understand what they are doing and the concept behind the labs. Labs are not meant to teach one grammar or how to write and abstract, because other labs are different and for a vast majority, labs do not require or want these items. class: I think this is a good lab set up overall. I would however change the first challenge's first day. Once again, talking with other students it seemed like they did not understand what they are suppose to be hypothesizing. I also would think that all the materials should be presented but just guide the class toward getting certain graphs with multiple materials.

- One of the best lab classes I have ever attended. No lie.

Please describe the aspects of this class that you most enjoyed:

- Using LoggerPro

- Applying concepts that were learned in lecture to help further develop my understanding of that concept.

- I liked that we used LoggerPro the whole time and didn't have to learn a new software every week. This way we were able to actually learn how to use the program.

- I enjoyed running tests on the cart using logger pro. I liked making the different bumpers out of paper and finding out what worked and what didn't. With each change you could see if you made a better or worse iteration of what you made.

- hands-on

- I liked getting to design your own bumpers

- Not being given exact instructions.

- Simple experiments that demonstrated concepts in physics clearly.

- The environment, working through problems in experiments, critical thinking.

Please identify any areas of improvement, or changes you wish to see, in the curriculum of this class:

- Make the first couple of weeks of this class less stressful.
- more instructions in the training activities to give a better understanding of what needs to be performed.
- Some of the instructions could be a little more detailed. Also, maybe some class time could be given to write the lab reports sometimes.
- Some of the things that the training activities asked us to do seemed vague and could use more explanation. Some of the things we were asked to do using LoggerPro seemed confusing to new users. Going more in depth on how to do things in LoggerPro would help.
- better description of what we are doing or hypothesizing
- More clear explanations of writing the lab reports
- More information given on what the lab reports should show

In summary, these student comments reinforce the feedback from instructors. The emphasis on writing, conceptual understanding, and critical thinking skills in a physics class surprised some students, who came in with expectations of a traditional expository laboratory with specific instructions and outcomes that hinge on verification of a mathematical relationship. Nevertheless, the next version of Mechanics, Inc. will incorporate this feedback with more clarity in setting expectations for the course and the particular activities.

Preliminary Assessment of Student Attitudes

Student perception of the course can be taken into account in formative assessment of the course, but because part of the intention of the Mechanics, Inc. curriculum is aimed at changing attitudes of students toward physics, an assessment of that affective dimension is also underway. Only preliminary data has been gathered, but in that effort an assessment instrument has shown to provide some results of interest.

This instrument is comprised of two parts. The first is the Maryland Physics Expectation (MPEX) survey[9], an established set of 34 statements about how students approach the study of physics. Preferred or favorable responses on a five-point Likert scale (from Strongly Disagree to Strongly Agree) are reported in the literature, based on responses from an expert group. The second part is the Curiosity and Exploration Index (CEI)[10], with seven statements about how students seek out new knowledge and become absorbed in an activity. To align with the MPEX, the original seven-point Likert scale was reduced to a five-point scale with a neutral middle response. The CEI is added to learn more about these students' attitudes toward acquiring knowledge. Assessing curiosity may speak to the hypothesis that the more they are curious and seek to explore, the more likely they will accept the inquiry format of an introductory physics laboratory. For the purposes of this analysis, responses indicating more curiosity will be regarded as favorable.

These surveys include statements that align into clusters. The CEI clusters include Exploration and Absorption. The latter measures the degree to which a student becomes totally absorbed in activities, while Exploration describes a striving for novelty and challenge. In the MPEX, the six clusters identified by its authors are Independence, Coherence, Concepts, Reality Link, Math Link, and Effort. To briefly describe these, low Independence is the belief that learning physics is essentially receiving information; low Coherence indicates that physics is a collection of scattered facts, and students with low scores in the Concepts cluster tend to see physics as a collection of formulas without the conceptual understanding behind them. On the other hand, students with strong Reality Link scores see physics as widely applicable to situations in life; students high in the Math Link cluster see the usefulness of math to describe physical relationships, and those with a high Effort score take initiative to gain understanding about physics.

The combination of the MPEX and the CEI was administered to two groups of students. The first group would have taken the introductory physics lab in the Spring term, just prior to deployment of Mechanics, Inc. in the Summer of 2014. The second group would have been involved in the Summer deployment of Mechanics, Inc. The first group, the Spring group, consists of students starting in the introductory physics sequence in the usual term, while the Summer group is off the usual sequence, perhaps because they are starting the physics sequence early with good math preparation from high school, or because they are behind the usual sequence due to issues with math, or withdrawing or failing in their first term in physics. Thus, the Summer group is roughly half the size of the Spring group.

In both cases, the survey was administered in the second semester of the introductory physics sequence, at the beginning of the following academic term (due to practical issues). The enrollments of these courses were thus mostly, but not be entirely those students who took the first semester course in the previous term. However, a few themes emerge from analysis of their responses that will inform revisions of the laboratory curriculum, and possibly drive reform of the classroom portion of the introductory physics sequence. This preliminary assessment data is therefore considered to be formative, and is not intended to evaluate the success of Mechanics, Inc. activities or design.

To present concise results, only cluster averages are shown here. Several survey items are associated with each cluster. First, the percentage of students with a favorable (and unfavorable) response to each statement or survey item is calculated, with neutral responses ignored. If the experts disagreed, then a favorable response is either Disagree or Strongly Disagree. The cluster score is found as the average of the percentages of items within each cluster. Table 2 provides a comparison between cluster analysis results for the two groups of students, along with upper level students taking the junior/senior level theoretical mechanics course.

Overall, the trends in these results are similar for the Spring and Summer groups. There is some difference between Spring and Summer, but given the preliminary nature of the assessment, statistical significance of these differences has not been established. The first theme that emerges is that the Reality Link is clearly the strongest among the MPEX clusters. Kettering University students are required to experience five or more co-op terms before graduation, and more than two thirds of students major in mechanical engineering or electrical engineering. They appear to be aware of the applications of the course content in both everyday life and their career direction. It is also clear that they are curious, especially in terms of the Exploration cluster, seeking out new ideas and knowledge.

Table 2. Cluster analysis of responses on the MPEX and CEI surveys

Cluster	***Spring Group (N = 89)***	***Summer Group (N = 45)***	***Upper Level Group (N = 10)***
MPEX: Independence	*Favorable; Unfavorable* 50%; 31%	*Favorable; Unfavorable* 36%; 47%	*Favorable; Unfavorable* 48%; 28%
MPEX: Coherence	50%; 30%	42%; 33%	61%; 19%
MPEX: Concepts	53%; 29%	44%; 39%	64%; 18%
MPEX: Reality Link	76%; 10%	61%; 20%	73%; 10%
MPEX: Math Link	57%; 21%	42%; 31%	60%; 16%
MPEX: Effort	59%; 21%	49%; 29%	72%; 12%
CEI: Exploration	79%; 5%	65%; 12%	75%; 8%
CEI: Absorption	57%; 15%	60%; 16%	50%; 20%

The weaker MPEX clusters for students in both groups appear to be Independence, Coherence, and the Math Link. These may tend to all be related to the maturity of the student, as one can imagine that a more independent learner would tend to also see the subject as a coherent whole, and use mathematics to serve the understanding of physics. To illustrate this, consider these MPEX items; the first is part of the Independence cluster, the second is from the Coherence cluster, and the third is from the Math Link cluster.

“All I need to do to understand most of the basic ideas in this course is just read the text, work most of the problems, and/or pay close attention in class.” *(experts disagree)*

“A significant problem in this course is being able to memorize all the information I need to know.” *(experts disagree)*

“If I don't remember a particular equation needed for a problem in an exam there's nothing much I can do (legally!) to come up with it.” *(experts disagree)*

The promise of Modeling Instruction and Cognitive Apprenticeship in addressing these areas of the practice of physics was the main attraction to incorporating these methods. Further revision of the curricular materials, and continued training in facilitation for instructors, is hoped to impact future groups of students.

Conclusions

Mechanics, Inc. is a laboratory curriculum set in the context of an ersatz technical consulting firm. The instructional design of Mechanics, Inc. has served the students with a gradual introduction to laboratory skills and writing a formal report through Training Activities for the first part of the term, while Client Challenges provide a setting for creativity in problem solving. Students have responded well to the flexibility of the inquiry format of the laboratory activities when guided by careful facilitation by instructors. Assessment in free-response format has provided direction for improving details of the activities, and preliminary results from the combination of the MPEX and CEI surveys have illuminated characteristics of the predominantly engineering-focused student population in this calculus-based introductory physics laboratory course. The curriculum taps into the pragmatic and curious traits of these students, and seeks to challenge the breadth of their view of what it means to do physics.

Bibliography

1. Domin, D. S., "A Review of Laboratory Instruction Styles," *Journal of Chemical Education*, **76** (4), 543-547 (1999).
2. Hofstein, A., Lunetta, V. N., "The Laboratory in Science Education: Foundations for the Twenty-First Century," *Science Education,* **88** (1), 28-54 (2003).
3. American Association of Physics Teachers, "The Goal of Introductory Laboratories," College Park, MD, 1997. Available online at URL http://www.aapt.org/Resources/policy/goaloflabs.cfm, accessed 28 January 2015.
4. American Association of Physics Teachers, “AAPT Recommendations for the Undergraduate Physics Laboratory Curriculum,” available online at URL http://www.aapt.org/Resources/upload/LabGuidlinesDocument_EBendorsed_nov10.pdf, accessed 30 January 2015.
5. There are many summer or short term programs described online. One example may be found at the University of Texas at Austin Applied Research Laboratories, URL http://www.arlut.utexas.edu/education/HS_apprentice.php, accessed 30 January 2015.
6. Wilson, B. G., Jonassen, D. H., & Cole, P., “Cognitive approaches to instructional design.” In G. M. Piskurich (Ed.), *The ASTD handbook of instructional technology* (pp. 21.1-21.22). New York: McGraw-Hill. (1993). Available from URL http://carbon.ucdenver.edu/~bwilson/training.html, accessed 18 December 2014.
7. Collins, A., Brown, J. S., Holum, A., "Cognitive apprenticeship: Making thinking visible." *American Educator* **15** (3), 6-11 (1991). pp. 6-11.
8. This description is paraphrased from the website of the American Modeling Teachers Association, URL http://modelinginstruction.org, accessed 18 December 2014.
9. Redish, E. F., Saul, J. M., Steinberg, R. N., “Student Expectations in Introductory Physics,” *Am. J. Phys.* **66,** 212-224 (1998).
10. Kashdan, T. B., Rose, P., Fincham, F. D., “Curiosity and Exploration: Facilitating Positive Subjective Experiences and Personal Growth Opportunities,” Journal of Personality Assessment **82**(3), 291-305 (2004).