New
Orleans JAZZED about Engineering Education

Scaling Up Project-based Learning for a Large Introductory Mechanics Course Using Mobile Phone Data Capture and Peer Feedback

Mr. John W. Sanders, University of Illinois, Urbana-Champaign

John W. Sanders is currently working toward a Ph.D. in Theoretical and Applied Mechanics at the University of Illinois at Urbana-Champaign, where he has served as the official instructor for an undergraduate-level, introductory dynamics course for the past two summers. He holds a B.S. in Engineering Physics and Mathematics from Saint Louis University, and an M.S. in Theoretical and Applied Mechanics from the University of Illinois at Urbana-Champaign. His research interests include solid mechanics, micromechanics of materials, fracture mechanics, and STEM education research.

Prof. Matthew West, University of Illinois, Urbana-Champaign

Matthew West is an Associate Professor in the Department of Mechanical Science and Engineering at the University of Illinois at Urbana-Champaign. Prior to joining Illinois he was on the faculties of the Department of Aeronautics and Astronautics at Stanford University and the Department of Mathematics at the University of California, Davis. Prof. West holds a Ph.D. in Control and Dynamical Systems from the California Institute of Technology and a B.Sc. in Pure and Applied Mathematics from the University of Western Australia. His research is in the field of scientific computing and numerical analysis, where he works on computational algorithms for simulating complex stochastic systems such as atmospheric aerosols and feedback control. Prof. West is the recipient of the NSF CAREER award and is a University of Illinois Distinguished Teacher-Scholar and College of Engineering Education Innovation Fellow.

Dr. Geoffrey L Herman, University of Illinois, Urbana-Champaign

Dr. Geoffrey L. Herman is a visiting assistant professor with the Illinois Foundry for Innovation in Engineering Education at the University of Illinois at Urbana-Champaign and a research assistant professor with the Department of Curriculum & Instruction. He earned his Ph.D. in Electrical and Computer Engineering from the University of Illinois at Urbana-Champaign as a Mavis Future Faculty Fellow and conducted postdoctoral research with Ruth Streveler in the School of Engineering Education at Purdue University. His research interests include creating systems for sustainable improvement in engineering education, promoting intrinsic motivation in the classroom, conceptual change and development in engineering students, and change in faculty beliefs about teaching and learning. He serves as the webmaster for the ASEE Educational Research and Methods Division.

Scaling-up project-based learning for a large introductory mechanics course using mobile phone data capture and peer feedback

Abstract

Project-based learning (PBL) has been shown to result in many benefits, including improved conceptual understanding and enhanced skills in communication, teamwork, and creativity, all widely acknowledged to be core capabilities for engineers. However, implementations of PBL frequently rely on large course staffs or small class sizes to be effective. In this paper we present a PBL implementation strategy used in an introductory dynamics course at the University of Illinois at Urbana-Champaign (UIUC), which scales up to 500 students per term. This large-scale usage of PBL relies on two key implementation strategies: (1) use of students' own mobile phones as the primary data capture devices, and (2) computer-mediated peer feedback for the majority of formative assessment. We present project results and student survey data that demonstrate the feasibility of large-scale PBL that achieves student learning outcomes without undue instructor burden.

1   Introduction

In project-based learning, projects are focused on questions that drive students to encounter concepts and principles which will result in transferable skills.[1,2] This transferable learning results in metacognitive improvements in how students acquire, process and synthesize information[3] as well as concrete skills such as teamwork, conflict resolution, and communication skills. Over the last quarter of a century, many research studies have demonstrated that PBL can improve learning outcomes related to highly structured understanding of the material and ability to transfer knowledge to new situations.[4] These outcomes are

- Enhanced understanding[5] and comprehension[6,7]
- More spontaneous venturing of ideas[8]
- More elaborate explanations that describe mechanisms and cause-effect relationships[9] or refer to personal experiences[10]
- Questions that focus on explanations and causes, predictions, or resolving discrepancies in knowledge and engaging in theorizing[8]
- Constructing more elaborate, well-differentiated knowledge structures[11]

While PBL affords many advantages in students' learning, it is rarely used because it is time consuming and difficult to implement well. A major hurdle in implementing project-based learning environments is that they require simultaneous changes in curriculum, instruction, and assessment—all of which are daunting to faculty members.[12] These barriers to implementing

PBL become magnified as student enrollment climbs and certain modes of instruction and assessment become unsustainable at larger scales.

Starting in 2012, the introductory mechanics sequence at UIUC has been the focus of a concerted redesign effort.[13,14] This redesign was carried out by a group of faculty working together as a mutually supportive Community of Practice[15,16] with support from both a college-level program[17] and an NSF program[18]. Key goals of the redesign have been to use technology to improve both the student and instructor experience, such as through the use of online homework and exams,[19,20] and to enable more authentic learning experiences, including the use of PBL.

In this paper, we present on our efforts to deliver a project-based learning experience in a core mechanics course for over 250 students per term with an expectation of further scaling the experience to over 500 students per term. The project is described in Section 2, and involves teams of four students designing and implementing an experiment to determine the drag coefficient of a ball from a sport of their choice (e.g., ping pong, tennis, soccer) and to match their experimental results to a computer simulation of the experiment. The primary data collection devices were students' own mobile phones, which were used for capturing video that was then analyzed with open-source software. This use of "Bring Your Own Device" (BYOD) is the first key scaling strategy that we used.

Section 3 describes the project implementation and results, including the use of peer feedback to provide detailed mid-project formative feedback to students, allowing and encouraging them to iterate on their experimental designs and analysis. The use of computer-based peer matching and rubric-based peer feedback system was the second key scaling strategy to accommodate large student numbers without undue instructor time commitment. Section 4 presents student survey data that measures students' own perceptions of the project and their learning outcomes. In analyzing this data and the project results, the two primary metrics of success used are (i) the instructors' ability to scale the project to large class sizes without undue time and effort, and (ii) the students' evaluation of how much they learned by doing the project. Section 5 presents conclusions and finds that scaling PBL to large class sizes is indeed feasible.

2 Project description

The project described in this paper concerns projectile motion, a concept ubiquitous to nearly all introductory mechanics courses. An object (such as a baseball) is thrown into the air with an initial position and an initial velocity, and its subsequent motion is predicted using the laws of physics. The two most significant forces acting on the object are gravity (the object's weight) and the drag force due to air resistance. The drag force is always directly opposed to the velocity of the object, and its magnitude is characterized by the dimensionless drag coefficient

$$C_D = \frac{F_D}{\frac{1}{2}\rho A v^2}, \tag{1}$$

where F_D is the magnitude of the drag force, ρ is the density of the fluid (in this case, air), A is the cross-sectional area of the object, and v is the object's speed. An important result in fluid dynamics is that the drag coefficient is a function only of the Reynolds number, Re, of the fluid flow about the object. In particular, for a range of Reynolds numbers ($10^3 \lesssim \mathrm{Re} \lesssim 10^5$)

characteristic of macroscopic projectiles, the drag coefficient is approximately constant at $1/2$. This means that the magnitude of the drag force is proportional to the square of the object's speed, and we may write

$$\mathbf{F}_D = -cv^2\hat{\mathbf{v}}, \tag{2}$$

where

$$c = \tfrac{1}{2}\rho A C_D \tag{3}$$

is a constant for a given projectile, and $\hat{\mathbf{v}}$ is the unit vector in the direction of the object's velocity. For the project, students were charged with determining this drag parameter c for a spherical ball from a sport of their choice. The questions of primary interest were

- Is it necessary to account for air resistance in sports?
- Assuming it is necessary to account for air resistance, how accurate is the theoretical model for the drag force given by (2)?
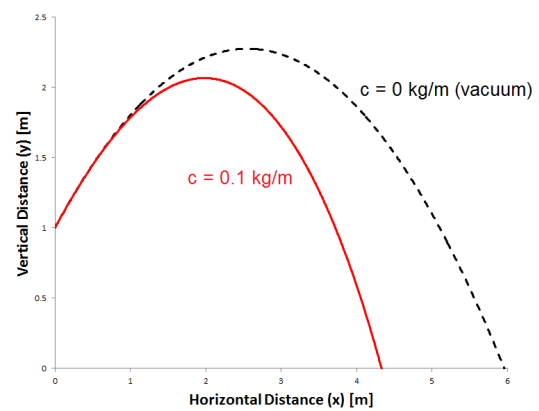
The project was divided into three parts: Analysis, Experiment, and Comparison.

2.1 Analysis

In Part 1 of the project, students were instructed to derive the equations of motion for a projectile near the surface of the earth in the presence of both gravity and drag, as given by (2). Emphasis was placed on thinking about the assumptions that went into deriving these equations. Because these equations have no closed-form solution, the students were told to solve the initial value problem numerically. In our case, most of the students were not familiar with numerical methods, so we had them implement a simple, forward time marching scheme in Microsoft Excel®. A sample spreadsheet, and a plot of the corresponding solution, are shown in Figure 1.

(a)   (b)

Figure 1. (a) Sample spreadsheet for Part 1 of the project, illustrating a numerical solution to the initial value problem of a projectile in the presence of both gravity and drag. (b) Corresponding plot of the projectile's trajectory (solid line), along with what the trajectory would have been in the absence of drag (dotted line).

2.2 Experiment

In Part 2 of the project, students were instructed to design a simple experiment to determine the drag parameter c for an arbitrary object. They were allowed to design any kind of experiment they wanted, provided that it could be done using common tools and measurement devices such as rulers, meter sticks, tape measures, stopwatches, weighing scales, force gauges, rope or string, a digital camera, video analysis software, etc. It was assumed that at least one student in each group would have access to some kind of digital camera, typically on his or her mobile phone.

Once they had finished their experimental designs, the students were instructed to perform their experiments on a spherical ball from a sport of their choice. They could choose between the following balls: ping pong ball, racquetball, tennis ball, cricket ball, baseball, softball, volleyball, soccer ball, basketball, and kickball. From their data, they were told to estimate the drag parameter c for their ball. They then used their estimate of c to compute the drag coefficient C_D by inverting (3). Additionally, the students were told to calculate a Reynolds number representative of their experiment, and to check that it fell in the appropriate range ($10^3 \lesssim \text{Re} \lesssim 10^5$).

2.3 Comparison

In Part 3 of the project, the students compared their experimental results from Part 2 to the corresponding theoretical predictions. Specifically, they compared their observed drag coefficient C_D to the theoretical value for a sphere, which is roughly $1/2$. They also compared their observed drag parameter c to its theoretical value, which is given by (3) with $C_D = 1/2$. Finally, they compared the results of their experiments to their analysis from Part 1 to see how close their numerical solution (now using their estimate for c) matched their experimental data.

Upon completing this project, we expect students to be better able to do, among other things, the following:

- Work collaboratively as part of a team
- Apply critical thinking skills to open-ended, real-world problems
- Design and perform their own experiments
- Identify assumptions they make when analyzing a problem
- Assess the validity of their assumptions
- Create and use Microsoft Excel® spreadsheets
- Solve differential equations numerically
- Collect data using commonly available devices
- Report experimental results using statistics
- Compare experimental results to theoretical predictions
- Assess the validity of a theoretical model
- Identify sources of error in an experiment

All of these are skills that either cannot be taught in a traditional lecture, or are best learned by experience.

3 Project implementation and results

The project described in Section 2 has been implemented during two semesters of TAM 212, an introductory dynamics course at UIUC. This course is part of a sequence of three introductory TAM courses, 210, 212, and 251, required by several engineering programs. Students in TAM 212 are typically freshmen and sophomore engineering students. Most of them have completed the calculus sequence, but have not yet taken a course in differential equations.

During fall and spring semesters, the course is divided between a traditional lecture, which is led by a professor and meets three times per week for one hour at a time over the course of sixteen weeks, and smaller discussion sections, which are led by graduate students and meet once a week for one hour at a time. Typical enrollment is ~250 students for fall semesters and ~500 students for spring semesters. During summer semesters, the course consists only of a traditional lecture, which is led by a graduate student and meets three times per week for two hours at a time over the course of eight weeks. Typical enrollment for the summer semesters is ~40 students. The project described here was first implemented in TAM 212 during the Summer 2015 semester, and then again in the Fall 2015 semester.

3.1 Summer 2015

During the Summer 2015 semester, TAM 212 was taught by a graduate student, who developed the project based on personal experience. There were a total of 37 students enrolled in the course. The students were given 7 of the 8 weeks of the semester to work on the project. On the second day of lecture, the students were divided into 10 groups, each of which was assigned a different ball of those mentioned in Section 2.2. During the first two weeks of lecture, the theory of projectile motion with drag was covered extensively in the context of particle kinetics (Newton's laws of motion). While the students were required to work on the project outside of class, they were encouraged to seek assistance from the instructor if needed. Additionally, various checkpoints were set up throughout the semester to ensure that students were making adequate progress. These checkpoints are summarized in Table 1.

Of particular interest here is the second checkpoint, at which the instructor checked each group's experimental design. At this point the instructor had a dilemma. On one hand, part of the point of the project is for the students to design and perform their own experiment, not to do an experiment

Table 1. Checkpoints used throughout the project to ensure adequate student progress.

| Checkpoint	Parts to be Completed	Deliverables
1	Part 1	Handwritten analysis, working spreadsheet
2		Description of experiment design / data to be taken
3	Part 2	Experimental data
4	Part 3	Estimates for c and C_D
5		Draft of report
6		Peer review feedback
7		Final report / spreadsheet

that is simply given to them. On the other hand, some experiments are better than others, and there is the risk of disillusionment if the student's experiment fails. Finding the right balance between giving students freedom to do the experiment they want to do, even if they fail, and giving them guidance if they are headed for failure, is extremely challenging. In this case, the instructor decided to take the following approach: If a group's experimental design seemed likely to give reasonable results, the instructor took no action. If, however, the group's experimental design seemed likely to give bad results, the instructor recommended an experiment of his own design.

In the end, most of the groups decided to follow the instructor's recommendation. This involved tossing the ball with various initial velocities, and recording the trajectories using a digital camera. (Regardless of the experiment they chose, the students were told to perform at least 30 trials, so not unsurprisingly, most groups used exactly 30 initial velocities.) Data points for all 30 trajectories were then extracted using open-source video analysis software such as Tracker[21] or ImageJ[22], and plotted in the spreadsheet from Part 1, alongside the corresponding numerical solutions with the same initial velocities. For each trajectory, the numerical value of the drag parameter c was varied until the numerical solution matched the experimental data as closely as possible. The students then computed the average and standard deviation of all 30 c-values obtained in this way. At the fourth checkpoint, the instructor checked each group's average c-value and, if it was orders of magnitude away from the theoretical value, the instructor recommended that the students go back, check their work, and, if necessary, do additional experimental trials.

The students presented their results in a formal, written report. After they had submitted the first drafts of their report (the fifth checkpoint), there was a peer review and feedback process (the sixth checkpoint) during which each student was given another group's report to critique. The students then revised their first drafts before submitting their final reports (the seventh and final checkpoint).

Table 2. Student project results from the Summer 2015 semester, along with the results of one-sided hypothesis tests performed by the instructor after final drafts had been submitted. The density of air used to calculate the theoretical values was 1.205 kg/m^3.

Sport	Ball Diameter [m]	Experiment Sample Size	Drag Parameter (c) [kg/m]			Attained Significance Level (p)	Consistent at the 0.01 Level?
			Mean	Standard Deviation	Theoretical Value		
Ping-Pong	0.0400	30	0.000347	0.0001364	0.000379	0.1025	YES
Racquetball	0.0570	30	0.000923	0.0009191	0.000769	0.1789	YES
Tennis	0.0686	30	0.001575	0.0011173	0.001113	0.0118	YES
Cricket	0.0650	25	0.002152	0.0015538	0.001000	0.0001	NO
Baseball	0.0760	30	0.003622	0.0020908	0.001367	0.0000	NO
Softball	0.0977	34	0.002322	0.0001580	0.002259	0.0101	YES
Volleyball	0.2134	30	0.260000	0.0250000	0.010778	0.0000	NO
Soccer	0.2200	30	0.011367	0.0162406	0.011451	0.4886	YES
Basketball	0.2440	29	0.018784	0.0093875	0.014086	0.0035	NO
Kickball	0.2540	30	0.017780	0.0224770	0.015265	0.2699	YES
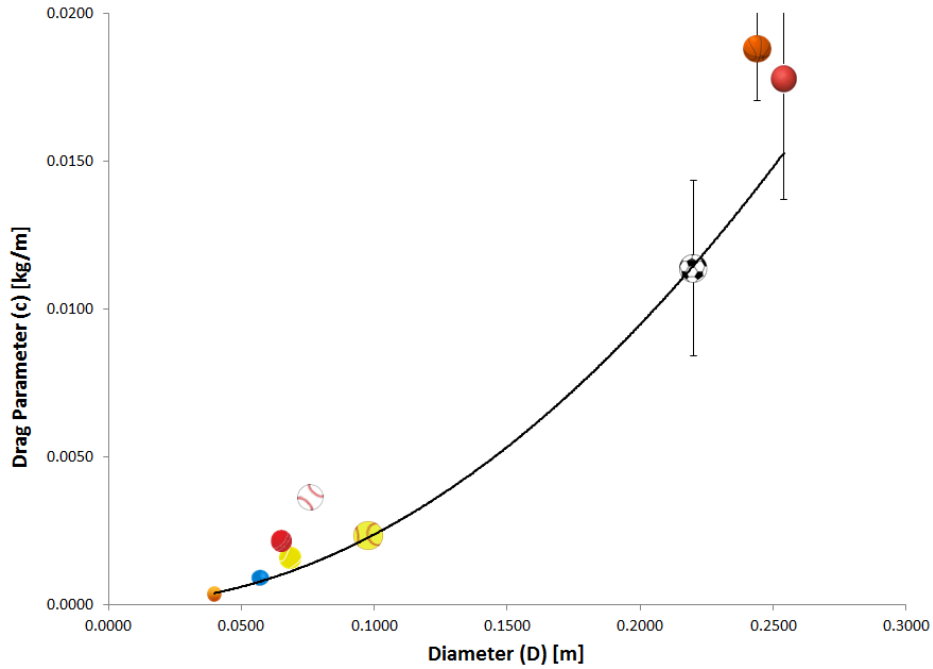
(a)
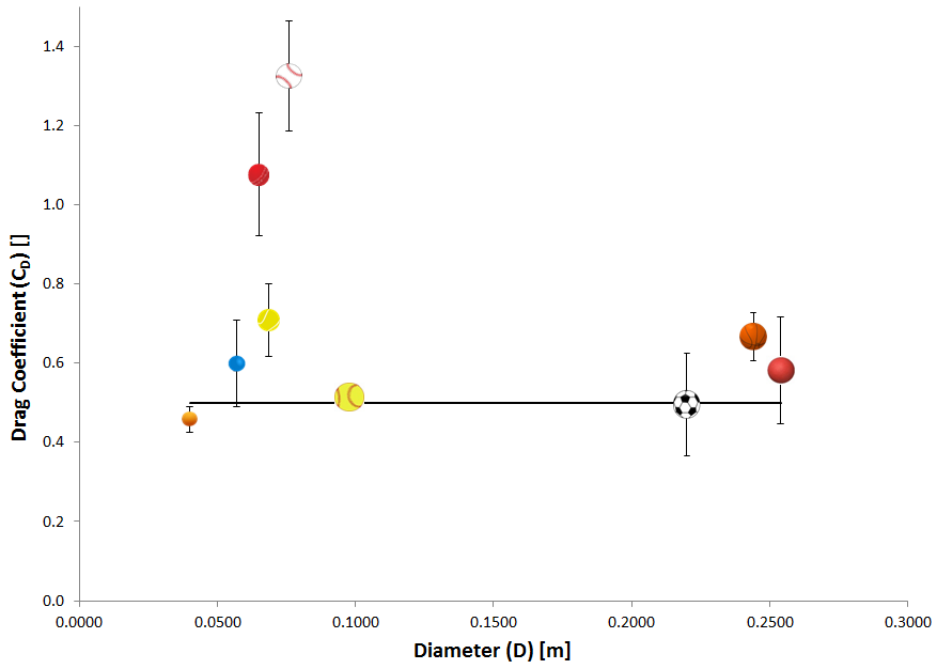
(b)

Figure 2. Student project results from the Summer 2015 semester. (a) Plot of mean drag parameter c for each group versus theoretical curve (solid black line). (b) Plot of mean drag coefficient C_D for each group versus theoretical value (solid black line). In each case, error bars represent a 68% confidence interval. The density of air used to calculate the theoretical values was 1.205 kg/m^3. See Table 2 for numerical data.

Once the final reports were submitted, the instructor performed a one-sided hypothesis test to determine how close each group's estimate for c was to its theoretical value. In these tests, the null hypothesis was that c was equal to the theoretical value, and the alternative hypothesis was that c was either greater than or less than the theoretical value (depending on the group's result). The results are shown in Table 2. Of the ten groups, six groups reported experimental results that were consistent with the theory at the $p = 0.01$ level. The instructor also plotted all ten groups' results for c and C_D against the theoretical trends, as shown in Figure 2. The instructor then shared these results with the students during the last lecture of the class.

3.2 Fall 2015

During the Fall 2015 semester, TAM 212 was taught by a professor, who had previously acted as a mentor to the graduate student instructor from the Summer 2015 semester, and was therefore familiar with the details of the project. There were a total of 234 students enrolled in the course, divided among 8 discussion sections. Each discussion section was further divided into approximately 8 groups. The students were given 12 of the 16 weeks of the semester to complete the project. Similar checkpoints to those listed in Table 1 were used this time, and many of them were chosen to coincide with the dates of discussion sections so that the students could use the discussion sections to work on the corresponding part of the project.

This time, the students were given more freedom to perform their own experiments, and the teaching assistants were instructed not to intervene if a group chose a poor experimental design. As a result, the students' estimates for the drag parameter and drag coefficient were generally farther from the theoretical values than they were in the Summer 2015 semester. Interestingly, though, the students reported that designing their experiments was one of their favorite parts of the project, according to the results of the end-of-semester survey (see Section 4).

The students again presented their work in a formal, written report, which they submitted online via Blackboard®. The peer review and feedback process was entirely automated. After the students submitted their first drafts, Blackboard® automatically assigned each student two other groups' reports to grade according to a rubric created by one of the teaching assistants, which is shown in Table 3. The students were able to submit their reviews, along with comments and suggestions, entirely online. The students then revised their first drafts before submitting their final reports.

4 Survey results and discussion

Near the end of the Fall 2015 semester, after the final project reports were submitted, the students were asked to complete a survey on their experience during the project. Of the 234 students enrolled in the course that semester, 190 responded to the survey, putting the response rate at just over 80%.

4.1 Likert scale questions

The first part of the survey consisted of several Likert scale questions, which assessed the students' perception of (i) how well working on the project improved their ability to perform

Table 3. Rubric used during the peer review and feedback process in the Fall 2015 semester

	QUESTIONS TO CONSIDER	SCORE			
		0	1	2	3
PART 1: THEORY	Is the group's derivation correct? Did they identify all of the assumptions they made? Are their assumptions reasonable? Is the spreadsheet set up in such a way that the input parameters can be varied easily? Are all base SI units labeled? Make suggestions as to how the derivation/spreadsheet could be improved.	Numerous errors. Many assumptions are unstated or unreasonable. The spreadsheet does not work.	Some errors. Some assumptions are unstated or unreasonable. The spreadsheet works, but is not user-friendly.	Few errors. Most assumptions are stated clearly and reasonable. The spreadsheet works and is user-friendly.	No errors. All assumptions are stated clearly and reasonable. The spreadsheet works and is very user-friendly.
PART 2(a): EXPERI-MENT DESIGN	Is the experimental design sound? If not, make suggestions as to how the design of the experiment could be improved.	The experimental design is not sound at all, and requires major improvement.	The experimental design requires significant improvement.	The experimental design is sound, but requires some improvement.	The experimental design is sound and requires no improvement.
PART 2(b): EXPERI-MENT IMPLE-MENTA-TION	Is the group's sample size sufficiently large? In other words, did they perform their experiment enough times that their data can be used to make meaningful estimates? Did the group report all the relevant statistics for the drag parameter (sample size, mean, standard deviation, etc.)? If not, which statistics need to be added, changed, or removed? Did the group report the mass and diameter of their ball, as well as an average Reynolds number? Are all base SI units reported? Make suggestions as to how the implementation of the experiment could be improved.	The sample size is far too small. Many parameters/statistics are omitted.	The sample size is too small. Most of the relevant parameters/statistics are reported.	The sample size is sufficiently large, but some relevant parameters/statistics are omitted.	The sample size is sufficiently large. All relevant parameters/statistics are reported.
PART 3: COMPARI-SON	Did the group identify all the sources of error in their experiment? Are their conclusions consistent with their observations? Make suggestions as to how the comparison could be improved.	Few, if any, sources of error are identified. Many conclusions are inconsistent with the observations.	Some sources of error are identified. Some conclusions are inconsistent with the observations.	Most of the relevant sources of error are identified. Most of the conclusions are consistent with the observations.	All sources of error are identified and accounted for. All conclusions are consistent with the observations.

various high-level PBL tasks, (ii) the difficulty of the project, (iii) how much time they were given to complete the project, (iv) the connection between the project and the lecture material, (v) how the skills they developed by doing the project will be useful in future science/engineering classes, and (vi) how the skills they developed by doing the project will be useful later in their careers. The responses to these questions are summarized in Figures 3-7.
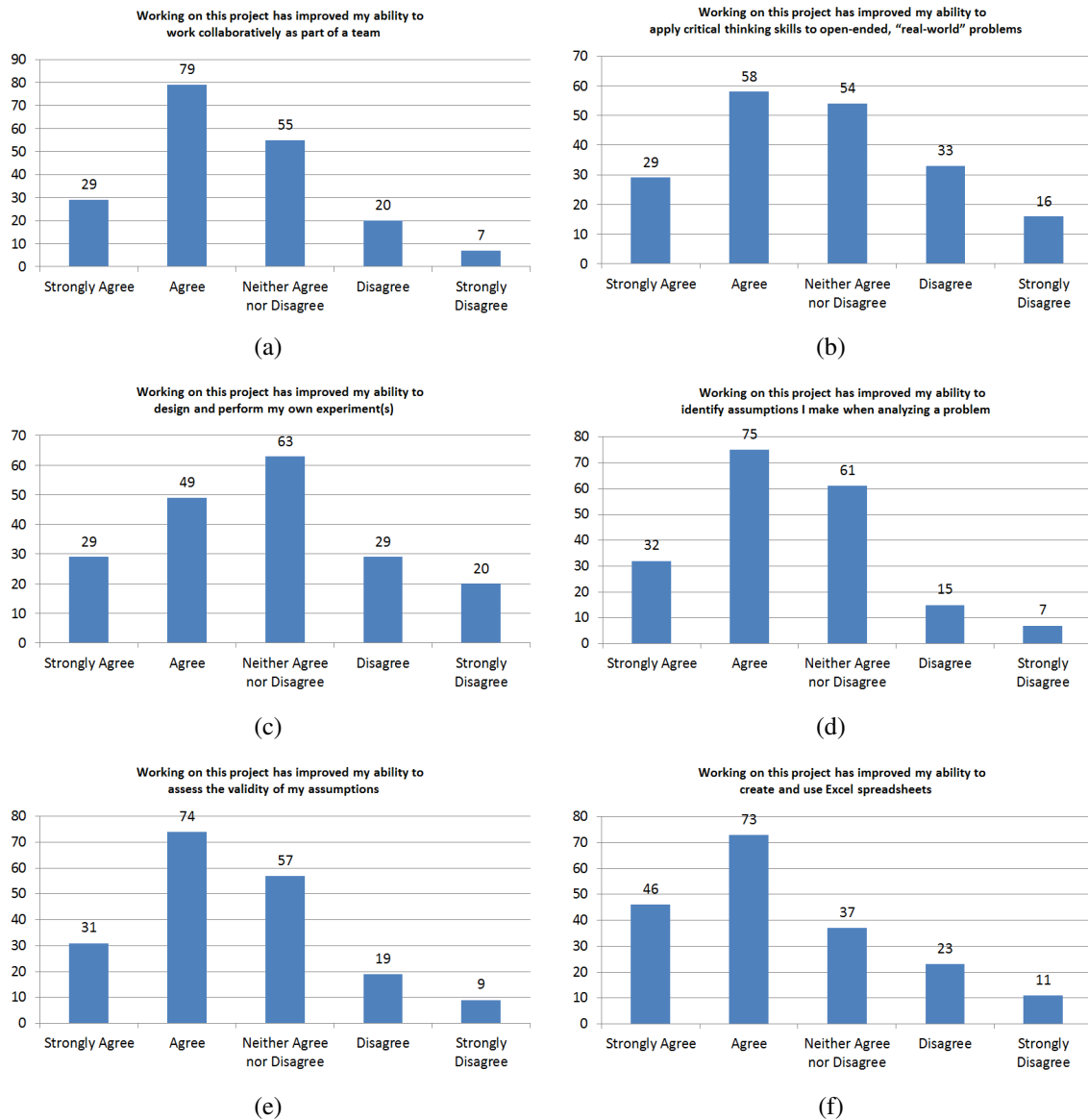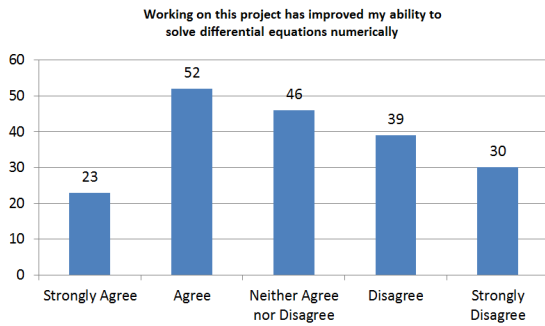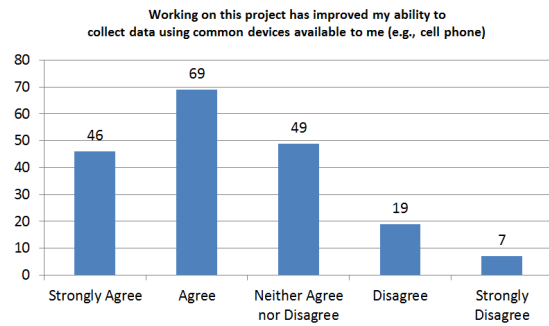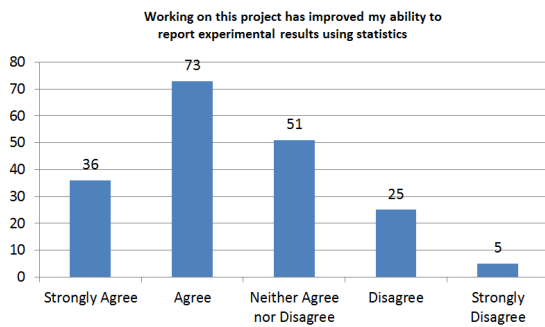

Figure 3. Survey results from the Fall 2015 semester, showing students' perception of how well working on the project improved their ability to perform various high-level PBL tasks.
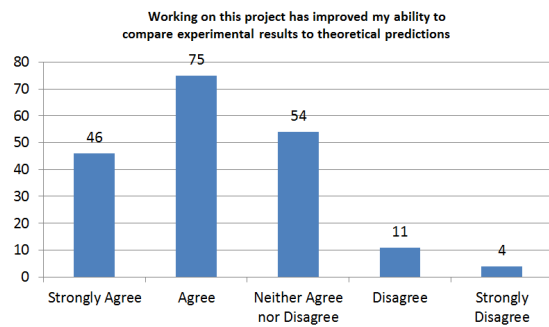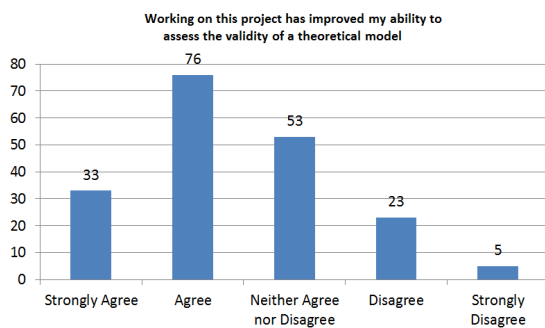
(a) Working on this project has improved my ability to solve differential equations numerically

Strongly Agree: 23, Agree: 52, Neither Agree nor Disagree: 46, Disagree: 39, Strongly Disagree: 30

(b) Working on this project has improved my ability to collect data using common devices available to me (e.g., cell phone)

Strongly Agree: 46, Agree: 69, Neither Agree nor Disagree: 49, Disagree: 19, Strongly Disagree: 7

(c) Working on this project has improved my ability to report experimental results using statistics

Strongly Agree: 36, Agree: 73, Neither Agree nor Disagree: 51, Disagree: 25, Strongly Disagree: 5

(d) Working on this project has improved my ability to compare experimental results to theoretical predictions

Strongly Agree: 46, Agree: 75, Neither Agree nor Disagree: 54, Disagree: 11, Strongly Disagree: 4

(e) Working on this project has improved my ability to assess the validity of a theoretical model

Strongly Agree: 33, Agree: 76, Neither Agree nor Disagree: 53, Disagree: 23, Strongly Disagree: 5

(f) Working on this project has improved my ability to identify sources of error in an experiment

Strongly Agree: 48, Agree: 71, Neither Agree nor Disagree: 46, Disagree: 19, Strongly Disagree: 6

Figure 4. Additional survey results from the Fall 2015 semester, showing students' perception of how well working on the project improved their ability to perform various high-level PBL tasks.
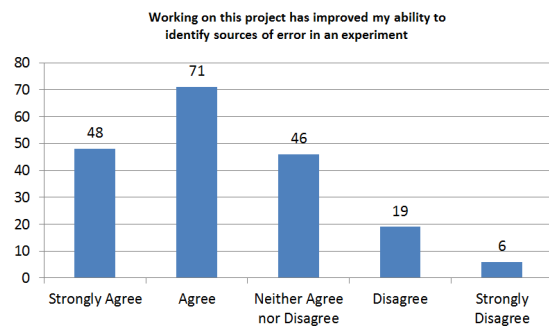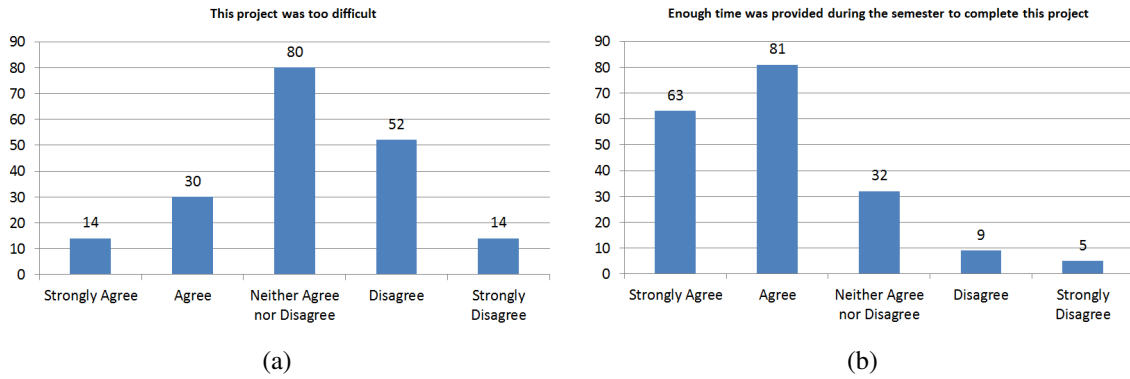
Figure 5. Survey results from the Fall 2015 semester, showing students' perception of (a) the difficulty of the project, and (b) how much time they were given to complete the project.
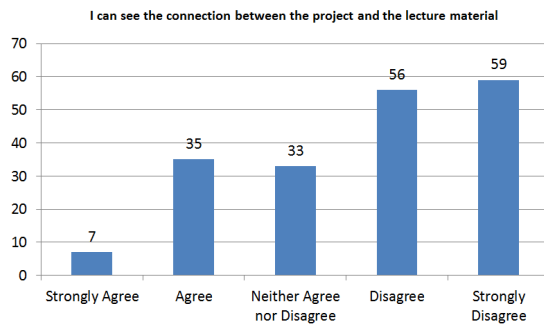

Figure 6. Survey results from the Fall 2015 semester, showing students' perception of the connection between the project and the lecture material.
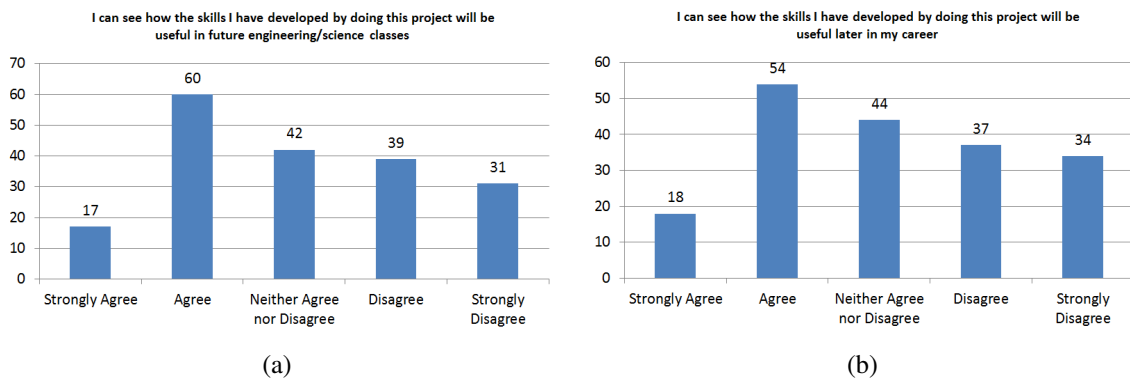

Figure 7. Survey results from the Fall 2015 semester, showing students' perception of how the skills they developed by doing the project will be useful (a) in future science/engineering classes, and (b) later in their careers.

Based on Figures 3 and 4, it appears that, on average, the students tended to agree that the project helped them develop the targeted skills. While individual students perceived different levels of improvement for the various skills, the very similar shape of many of the histograms in Figures 3 and 4 suggests that, overall, the skills were given nearly equal emphasis. From Figure 5, the perceived difficulty of the project was almost normally distributed, which is ideal. If anything, a few more students thought that the project was too easy. Additionally, the majority of students felt that 12 weeks was enough time to complete the project. From Figure 6, it is clear that the majority of students did not see the connection between the project and the lecture material. While disconcerting, this can be attributed to the instructor's decision to delegate the project-related material to the discussion sections, rather than spending a significant amount of time on it in lecture. Finally, from Figure 7, it can be seen that the class was somewhat evenly distributed among those who could see how the project would be useful later on in their studies and future career, and those who could not.

4.2   Free-response questions

The second part of the survey consisted of three free-response questions, which asked the students to describe their favorite part of the project, their least favorite part of the project, and what, if anything, could be done to improve the project. The top five most common responses to each of these questions are shown in Figures 8 and 9.

It is clear from Figure 8 that the students enjoyed performing their experiments more than anything else. They also enjoyed working in groups, designing their experiments, and learning the theory behind the project. Their single least favorite aspect of the project was the lack of a clear connection to the other course material. They also did not enjoy the lack of guidance they received, analyzing their data (particularly using the video analysis software Tracker), and writing the report. There was some polarization in regard to Excel®, with 19 students reporting that it was one of their favorite parts, and 20 students reporting that it was one of their least favorite parts. This is likely attributable to the extent of each individual's prior experience with Excel®.
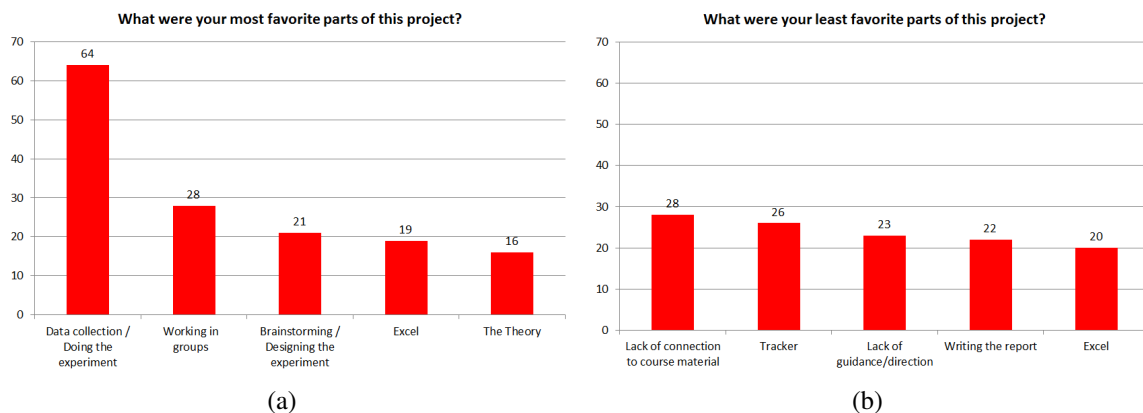

Figure 8. Survey results from the Fall 2015 semester, showing (a) the students' five most favorite parts of the project, and (b) the students' five least favorite parts of the project.
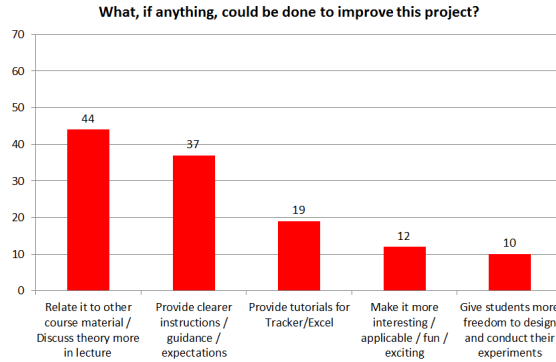
Figure 9. Survey results from the Fall 2015 semester, showing the top five student suggestions for how to improve the project.

Finally, from Figure 9, the number one suggestion for improvement is to provide a clearer connection between the project and the rest of the course material. To that end, we believe that the following would be beneficial: discussing the theory more in lecture, including project-related questions on the homework, quizzes, and exams, and making the project a greater percentage of the total course grade. Other suggestions from the students included providing clearer instructions/guidance/expectations, providing tutorials for Excel® and Tracker, making the project more interesting/exciting, and providing the students more freedom to conduct their own experiments. The latter is interesting, given that the instructor specifically emphasized this freedom. From reading the responses in detail, it seems that, because the students designed their experiments during one of the discussion sections (that is, in close proximity to other groups), some of them were tempted to copy other groups' experimental designs. This can be easily remedied by having the students design their experiments outside of the discussion section.

5   Conclusion

We have described here an implementation of project-based learning in an introductory dynamics course at the University of Illinois at Urbana-Champaign over the course of two semesters. The project was successfully scaled from a class of ~40 students in the summer to ~250 students in the fall. Two implementation choices were particularly important for this success. The first was the use of devices already in the students' possession (such as their mobile phones) to collect the necessary data. This "Bring Your Own Device" (BYOD) approach allows cost-free scaling of PBL experiments to very large student numbers, and it is also empowering when students realize that they already have the capability to collect meaningful data.[1] Second, a computer-based peer matching system was used for the peer review and feedback process, which can accommodate a class of any size at no additional cost to the instructor. Ultimately, scaling the project from the summer to the fall semesters resulted in no additional cost beyond the presence of additional

---

[1]It should be noted that this approach only works if students do, in fact, already have the tools they need. For example, the success of the project described here depended on the assumption that at least one student in each group owned a digital camera, if only on his or her mobile phone. Access to a computer was also necessary, but in this case the university already had a number of computer labs open to students. Clearly, scaling up this particular project would not be feasible in settings where students do not have access to digital cameras and computers.

teaching assistants (which were already necessary for the discussion sections independently of the project). Additionally, the results of an end-of-semester survey indicate that, on average, students believe that the project is helping them develop the high-level engineering skills targeted by PBL. We conclude that scaling PBL to large class sizes is indeed feasible, and we look forward to scaling the TAM 212 project to even greater numbers in the spring.

Acknowledgments

Bibliography

[1] M. M. Lombardi. Making the grade: The role of assessment in authentic learning. *EDUCAUSE Learning Initiative*, 2008.

[2] J. Reeve. Why teachers adopt a controlling motivating style toward students and how they can become more autonomy supportive. *Educational Psychologist*, 44:159–175, 2009.

[3] F. Marton and S. Booth. *Learning and Awareness*. New York: Lawrence Elbaum Associates Inc., 1997.

[4] J. B. Biggs. *Teaching for Quality Learning at University*. Maidenhead: Open University Press, 2nd edition, 2003.

[5] G. M. Bodner. Constructivism: A theory of knowledge. *Journal of Chemical Education*, 63:873–878, 1986.

[6] W. H. Leonard and J. E. Penick. How do college students best learn science? *Journal of College Science Teaching*, 5:385–388, 2000.

[7] E. Von Glasserfield. Learning as a constructive activity. In C. Janvier, editor, *Problems of Representation in the Teaching and Learning of Mathematics*. New Jersey: Lawarence Erlbaum Associates, 1987.

[8] C. Chin and D. E. Brown. Learning deeply in science: An analysis and reintegration of deep approaches in two case studies of grade 8 students. *Research in Science Education*, 30(2):173–197, 2000.

[9] M. J. Entwistle. The use of research on student learning in quality assessment. In G. Gibbs, editor, *Improving Student Learning, through Assessment and Evaluation*. Oxford: The Oxford Centre for Staff Development, 1990.

[10] S. D. Brookfield. *Developing Critical Thinkers: Challenging Adults to Explore Alternative Ways of Thinking and Acting*. San Francisco: Jossey Bass, 1985.

[11] N. R. Pearsall, J. E. Skipper, and J. J. Mintes. Knowledge restructuring in the life sciences: a longitudinal study of conceptual change in biology. *Science Education*, 81:193–215, 1997.

[12] B. J. Barron, D. L. Schwartz, N. J. Vye, A. Moore, A. Petrosino, L. Zech, and J. D. Bransford. Doing with understanding: Lessons from research on problem- and project-based learning. *Journal of the Learning Sciences*, 7(3-4):271–311, 1998.

[13] M. West and G. L. Herman. Sustainable reform of "introductory dynamics" driven by a community of practice. In *Proceedings of the 121st American Society for Engineering Education Annual Conference and Exposition (ASEE 2014)*, 2014.

[14] M. West, M. Silva Sohn, and G. L. Herman. Sustainable reform of an introductory mechanics course sequence driven by a community of practice. In *Proceedings of the ASME 2015 International Mechanical Engineering Congress & Exposition (IMECE 2015)*, 2015.

[15] M. West and G. L. Herman. Mapping the spread of collaborative learning methods in gateway stem courses via communities of practice. In *Proceedings of the 122nd American Society for Engineering Education Annual Conference and Exposition (ASEE 2015)*, 2015.

[16] M. West, M. Silva Sohn, and G. L. Herman. Randomized exams for large stem courses spread via communities of practice. In *Proceedings of the 122nd American Society for Engineering Education Annual Conference and Exposition (ASEE 2015)*, 2015.

[17] L. Crowley and G. L. Herman. Using faculty communities to drive sustainable reform: Learning from the strategic instructional initiatives program. In *Proceedings of the 121st American Society for Engineering Education Annual Conference and Exposition (ASEE 2014)*, 2014.

[18] G. L. Herman, I. B. Mena, M. West, J. Mestre, and J. H. Tomkin. Creating institution-level change in instructional practices through faculty communities of practice. In *Proceedings of the 122nd American Society for Engineering Education Annual Conference and Exposition (ASEE 2015)*, 2015.

[19] M. West, G. L. Herman, and C. Zilles. Prairielearn: Mastery-based online problem solving with adaptive scoring and recommendations driven by machine learning. In *Proceedings of the 122nd American Society for Engineering Education Annual Conference and Exposition (ASEE 2015)*, 2015.

[20] C. Zilles, R. T. Deloatch, J. Bailey, B. B. Khattar, W. Fagen, C. Heeren, D. Mussulman, and M. West. Computerized testing: A vision and initial experiences. In *Proceedings of the 122nd American Society for Engineering Education Annual Conference and Exposition (ASEE 2015)*, 2015.

[21] D. Brown. Tracker Video Analysis and Modeling Tool, 2015. Available: http://physlets.org/tracker/.

[22] ImageJ Image Processing and Analysis in Java, 2016. Available: http://imagej.nih.gov/ij/index.html.