

Teaching Physics Concepts without (Much) Mathematics: View through a Concept-Index, Threshold Concept Lens

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STRUCTURED ABSTRACT

CONTEXT

In 2018, the Faculty of Science and Engineering at the University of Waikato has introduced an option for first-year physics study that does not require achievement at high-school physics and mathematics. This offering uses a style of teaching physics newly introduced to the University of Waikato that features minimally-mathematical teaching, hands-on exploratory experiments, and concept-index-style assessment. The course is one adapted from work pioneered at Rutgers University. In this work we report on its implementation and its success.

PURPOSE

We are looking to see if students 'get the ideas', and staff are able to assess this understanding, without substantial mathematical problem-solving and numerical assessment questions. We are also interested in engagement and satisfaction on the part of the students.

APPROACH

In addition to a few simple numerical examples worked in tutorials and numerical results measured using instruments in lab classes, students are asked to answer "What happens if..." and "How do I get..." questions through educated trials carried out in laboratory groups. The work emphasizes the process of scientific enquiry as much as the ideas themselves. We tested students with multiple-choice, non-numeric questions in the style of "concept indices" such as the Force Concept Index (FCI) and the Signals and Systems Concept Index (SSCI). We interviewed students to obtain their reaction to this style of physics teaching, and to discover if they felt they were learning and understanding. We interviewed teachers to obtain comparative impressions with "old-style" physics teaching. In order to improve gender diversity, the material in the course used female names for fictitious characters and highlighted the work of female physicists.

RESULTS

It appears that student engagement is significantly improved. Teacher satisfaction is surprisingly increased. Initial impressions from student feedback suggest that the process of scientific enquiry through experiment is actually alien to some of the students, despite many being enrolled in science degrees. In a post-course test, students achieved 60% of the maximum possible gain from a similar pre-course test, a result consistent with the best interactive approaches. Approximately 20% of the participants were female, higher than other physics papers offered in recent years at the University of Waikato.

CONCLUSIONS

While it remains to be seen if the concept-based education delivered in this style of course proves to be sufficient grounding for successful progress in engineering and scientific degree streams, it is already clear that student satisfaction increases.

KEYWORDS

Concept-Index, Physics, Mathematics.

Introduction

Through student-led practical classes, the Investigative Science Learning Environment (ISLE) is demonstrated to successfully achieve student learning outcomes in physics (Etkina, Murthy and Zou, 2006; Etkina and Van Heuvelen, 2007). ISLE calls for strong focus on modelling the methods of science applied by professional scientists – for example making observations, testing hypotheses, and applying understanding through experiments (Etkina and Planinšič, 2014; Poklinek Čančula, Planinšič and Etkina, 2015). ISLE is student-led; meaning that explicit instructions on how to perform teaching experiments are not given. This contrasts vividly with the 'cookbook' approach to student laboratories, still practised at many universities including the University of Waikato. An integral part of ISLE is a 'Symposium', in which students discuss with other students how they have tackled an experiment and learn from their peers. While ISLE has had proven success with large classes of physics-major students predominantly in the United States, it has had limited demonstration in other contexts.

In 2018, The University of Waikato introduced a first-year paper APHYS111 Physics in Context, designed to support students completing science majors in disciplines other than physics. The paper has been designed to be as accessible as possible, meaning there are no prerequisites beyond what is required for entrance to a New Zealand university in general. Consequently, the paper presents physics from a concepts perspective, as opposed to a mathematics perspective. Moreover, ISLE has been chosen as a model for the experimental work in this paper. This situation has provided an excellent opportunity to study the acquiring of learning outcomes in physics through an investigator-led, concept-based approach, with a small group of non-physics-major students in a New Zealand context.

The APHYS111 paper, as run in 2018, consisted of lectures and tutorials (often mixed together), and laboratory sessions, with strong emphasis on the laboratory sessions. Students were assessed through four assignments (including two numerical assignments, an essay and a group oral presentation), seven laboratory sessions, two tests, and an exam. Students worked in the laboratory in groups of three or four. Only seven laboratory sessions were possible for 2018 in a twelve-week semester. This was due to lack of funding from the hosting department, which reflected a general lack of buy-in among our engineering colleagues for this paper. A conscious effort was made to include examples of the work of female physicists and to ensure that all 'fictional characters' in the laboratory manual were female. Indeed, the ISLE material on its own does well in this regard.

In this paper, we present research carried out in A-semester 2018 with the APHYS111 paper. We have assessed student skills and knowledge before and after the paper using concept tests and have analyzed their acquiring of experimental skills as they progress. Interviews with students and teaching staff have also been conducted to bring in their experiences of the paper.

Approach

We have used several measures of student learning in this study. First, we used pre-course and post-course testing. Students undertook two ten-question multiple-choice tests, one at the start of the course and one at the end. The questions covered topics taught in the paper, specifically mechanics, thermodynamics, electricity & magnetism, vibration & waves, optics & quantum physics, and nuclear physics & the universe, which were taught in that order. They were formulated conceptually – no calculations were required – along similar lines to well-used indices such as the Force Concept Inventory (Hestenes, Wells and Swackhamer, 1992) and the Signals and Systems Concept Inventory (Wage et al., 2005), which directly informed some of the questions. The multiple-choice tests were implemented on an IF-AT scratch-card, meaning that students received instant feedback as to whether they were correct. They were permitted to have multiple attempts at a question and scored 5, 2 and 1, for correct answers first time, second time and third time respectively. This gave a total mark out of 50. Questions in the post-course test covered exactly the same concepts as in the pre-course test, either by asking the same question in a different way, or by asking a new question but on the same concept.

Secondly, we have analyzed the students' laboratory skills as demonstrated by the records in their laboratory logbooks. We used the explicit assessment rubrics of ISLE (Etkina, Van Heuvelen, White-Brahmia, Brookes, Gentile, Murthy, Rosengrant and Warren, 2006; Etkina and Van Heuvelen, 2007). These cover the three distinct forms of scientific experiment – observation, testing and application. We also wrote our own rubric in similar form to cover general laboratory skills: the ability to keep a good

record of what was done; the ability to demonstrate the thinking behind a chosen method; the ability to make accurate measurements; the ability to record the results accurately; and the ability to make sense of what was done. Students' logbooks were assessed on the basis of how well the students had demonstrated these skills; each skill was assessed as 'missing', 'inadequate', 'needing improvement' or 'adequate'. We identified how many students had reached the 'adequate' (or halfway between 'needs improvement' and 'adequate') level for each of the skills, for each of the seven laboratory sessions.

Thirdly, a focus group of students was conducted by someone unconnected with the paper, after teaching had finished, but before the examination. Students were asked for their opinions on the paper and to identify how the paper had run and how it might be improved. About half the students attended the focus group. About half the attendees had not studied physics at all in their final years of high school, and acknowledged that they were unable to compare this course with other physics courses.

The university-administrated online evaluation of the paper has also been considered. Students have had the opportunity to submit answers to seven questions about the paper, specifically about accuracy of information, learning opportunities, assessment tasks, paper content, paper design, organization and overall experience. A four-point Likert Scale was used: 'Strongly Agree', 'Agree', 'Disagree', 'Strongly Disagree' with also an option 'Not able to judge'. Students were also asked for free responses to the questions "What aspects of the paper helped you learn?" and "What improvements could be made to this paper?"

Finally, teaching staff (two lecturers and a laboratory demonstrator) were asked for their experiences.

Results and Discussion

Student demographics

Of 28 students enrolled initially, 23 finished the paper. Those who dropped out did so early in the semester, and mostly from all subjects. All five of the female students initially enrolled completed the paper. Approximately one third of students had the intention of majoring in chemistry, approximately one third wanted ultimately to gain entry into engineering but lacked the prerequisites to do so, and the remaining third were majoring in a mix of other mostly scientific subjects, including computer science, earth science, biological science, psychology and education.

Pre- and post-course testing

Seventeen students completed both a pre-course test and a post-course test. Figure 1 shows the results, presented as percentages. In Figure 1(a) the marks for the post-course test are plotted against the marks for the pre-course test for each of the 17 students. Figure 1(b) shows the same data in terms of the gain for each student, where the % gain is defined as post-course test score (%) minus the pre-course test score (%). Also indicated are dotted lines denoting various 'g' values (Hake, 1998). A g-value denotes the fraction of the maximum possible gain achieved, that is:

$$g = [\text{Post-course score (\%)} - \text{pre-course score (\%)}] / [100\% - \text{pre-course score (\%)}],$$

so that $g = 1$ denotes that the maximum possible gain has been achieved and $g=0$ denotes no improvement. It is possible for g to be negative, denoting a poorer performance in the post-course test than the pre-course test. The 'g-value' is useful since it accounts for students having different pre-course knowledge across different topics.

The mean g-value is 0.61, shown by the dark dotted line. Figure 1(c) and Figure 1(d) show histograms of the pre-course and post-course test results respectively for the 17 students who completed both.

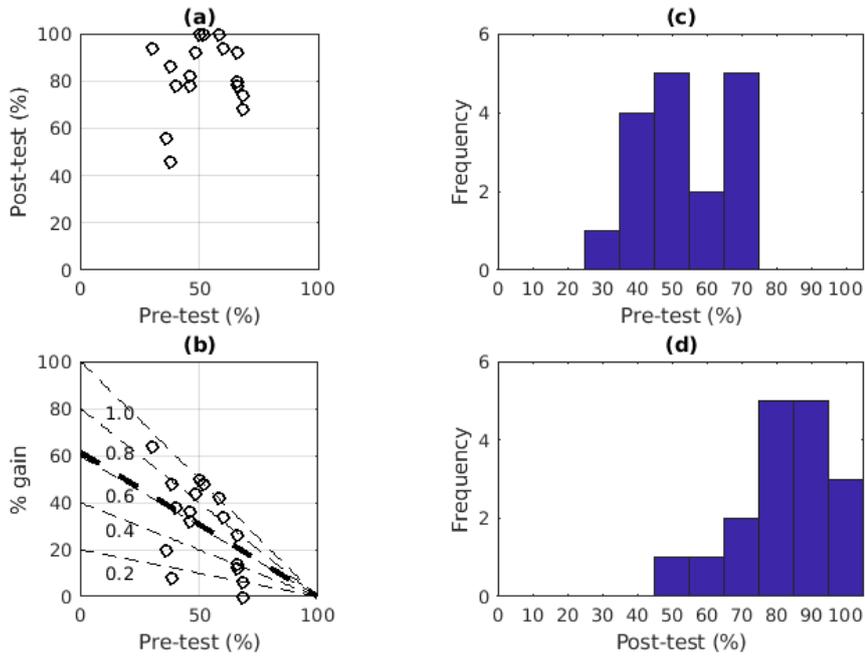


Figure 1: Results of the pre- and post-tests. (a) The post-test score of each student against their pre-test score. (b) The percentage gain of each student against their pre-test score. The thin dotted lines denote normalized gains of 0.2, 0.4, 0.6, 0.8 and 1.0. The thick dotted line denotes the mean normalized gain of 0.61. (c) A histogram of the pre-course test results. (d) A histogram of the post-course test results.

A large improvement has occurred between the pre-course test [Figure 1(c)] and the post-course test [Figure 1(d)]. Sixteen students improved in the post-course test; one obtained the same mark as the pre-course test. No students did worse in the post-course test. The 'g' averaged across students of 0.61 is similar to the 'g's demonstrated by the best performing interactive courses in Hake's classic assessment of 62 introductory university physics courses (1998).

A breakdown of the improvement is shown by topic area in Table 1, presented in the order in which the topics were taught.

Table 1: Gain in score for each topic averaged across students and questions on the topic

Topic	Questions on topic	Mean 'g'
Mechanics	2	0.22
Thermodynamics	2	0.55
Electricity & Magnetism	1	0.60
Vibration & Waves	1	0.40
Optics & Quantum Physics	2	0.87
Nuclear Physics & The Universe	2	0.85

Student improvement was greatest on concepts that were taught towards the end of the course. For example, the two mechanics questions obtained an average 'g' of +0.22, but the two optics & quantum physics questions had an average 'g' of +0.87. Possibly this is due to the later topics being in more recent memory. However, in contrast to this we note that the 'Mechanics' question of the end-of-semester examination was the best answered question on the exam paper, and 'Nuclear Physics & The Universe' the worst answered question.

Acquiring of laboratory skills

Laboratory sessions were assessed using rubrics. Five general skills were assessed for each experiment, plus other skills depending on whether experiments were observation, testing or application. The first six lab sessions included some kind of hypothesis testing, along with other forms of experiment. Figure 2(a) considers general laboratory skills, and plots the percentage of students who demonstrated or nearly demonstrated these skills adequately against the laboratory number (arranged chronologically so that higher lab numbers denote labs that were done later in the semester). Figure 2(b) does the same for skills associated with testing hypotheses; note that there was no 'testing' part to the laboratory work in the seventh session.

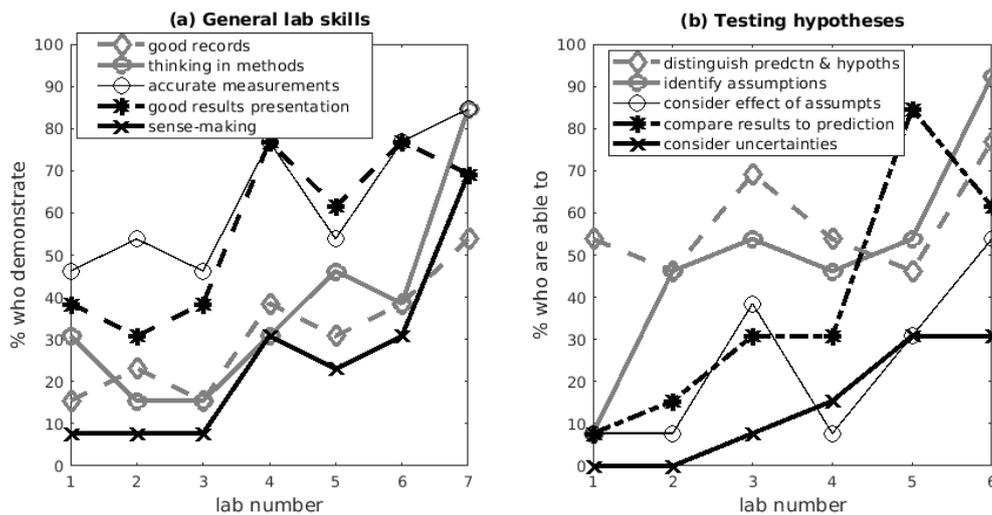


Figure 2: Acquiring of specific laboratory skills. (a) Plots of the percentage of students who demonstrated, or almost demonstrated, five specific general laboratory skills, against the lab number. The first lab students did is marked as '1', the second '2', and so forth, so that the x-axis represents increasing time into the semester. (b) Plots of the percentage of students who demonstrated, or almost demonstrated, five specific skills related to testing a hypothesis, against the lab number.

While there is some considerable variation from session-to-session, it is clear that all skills were demonstrated better in the latest lab sessions 6 and 7 than in earliest lab sessions 1 and 2. Of particular note is the large improvement in the ability of students to make sense of their work as the semester progressed, that is, being able to discuss what the experiment means [thick black curve of Figure 2(a)], and the ability of students to consider the effect of uncertainties in their measurements [thick black curve of Figure 2(b)].

Early on in the semester students struggled with keeping a good record of what was done in the laboratory. They were confused as to what was expected in the laboratory books, and what the marking rubrics supplied to them actually meant in terms of what to write down in the books.

Focus Group

Students identified laboratory work as a major component of this paper, and recognized the emphasis that had been put on the laboratories by the teaching staff. There was a consensus that other teaching sessions (e.g. lectures) should be held in the laboratory space. Students also wanted more laboratory sessions than just the seven we were able to implement for this first year, and to get the chance to use more advanced equipment.

Students felt they needed explicit teaching in how to keep a laboratory notebook. At the start of the course they were very unclear as to what it should contain. Some thought that an entire lecture should be devoted to explaining this. Also, the students expressed difficulty in formulating a hypothesis and developing experiments by which to test a hypothesis. Explicit guidance on this skill was requested. These comments are consistent with the plots of Figure 2(a), which show poor ability

to keep a good record of an experiment at the beginning of the paper, and Figure 2(b), which show difficulty in undertaking testing experiments.

There was some surprise expressed as to the content of this paper. Those students who had studied physics at high school thought that the content was very similar, but reported that the emphasis at school had been on putting in the time to do the experiments and getting the correct numerical outcomes. In contrast they recognised that APHYS111 placed emphasis on writing up what you had done. One student commented that this paper was “about describing everyday things in physics language”. This difference is indeed one that was intended by the design of the paper. However, we acknowledge that the work of professional scientists involves more skills than simply record-keeping.

Students identified the ability to break a problem down into smaller parts as a learning outcome they had achieved, although this was not explicitly listed as a learning outcome on the paper. Most students acknowledged that they had achieved a lot intellectually, for example:

“I learnt that I thought I understood, but then I learnt that I didn’t, and now I think I do.”

“I did not expect to get so much, I only spent about 3 hours on this.”

Students were also surprised to learn that physics at university is normally taught in a much more mathematical way. Students were pleased with the paper, although they thought it could be more “fun”.

Evaluations

Fifteen students completed the online evaluation of the paper. Of the seven questions asked, six had a positive modal response of "Agree". However, the question "The paper design helped me to examine different theories, concepts and practices" had a modal response of "Strongly Agree", suggesting that students recognized that this paper addressed concepts in physics as opposed to the mathematical content. Free responses were consistent with this:

"I enjoyed the real world applications of what we were learning."

"...what was being learned was very interesting and fun to participate [in]..."

Asked "what improvements could be made with this paper?", ten out of thirteen comments focused on the laboratories, and six of these on the amount of writing that students perceived to be necessary.

"...in the beginning [writing in the lab books] was a hindrance to learning."

There was only one specific comment on the mathematics:

"A lot of time was dedicated to teaching what was already easy maths"

Overall, it is clear from the evaluations that students have correctly recognized the value of the conceptually-based laboratory work to their learning (Etkina and Planinšič, 2014) and have singled out the keeping of a laboratory book as a troublesome area for them.

Teacher experiences

An external observer of the laboratory class reported sensing a high level of engagement. The most apparent measure of this was the low usage of mobile devices for external activity, although many were visible on the benches. Analysis in other classes suggests that even the highest-performing students could be expected to spend about 8% of their time on a mobile device even when the class gave no reason for such activity (Peter et al, 2017).

Overall, the teachers enjoyed the experience of developing and implementing this course for the first time. Although it was a considerable amount of effort, seeing first-hand the student learning happen in the laboratory was rewarding. Covering the laboratory material in class reinforced this experience, and one lecturer has started using this technique in another, more advanced, course.

There were many challenges faced. First, students had a wide range of abilities in maths and physics. Some students found basic algebra (for example "rearrange $a=bc/d$ for c ") a challenge; others were familiar with some concepts in calculus.

Secondly, the varied backgrounds of students created challenges for development of engaging laboratory and lecture sessions. For a paper entitled 'Physics in Context' it was clear that examples of physics should be drawn from all areas of science and beyond, but while some examples resonated with some students, others were left struggling. For example, those with chemistry backgrounds engaged well with the nuclear physics section, but many others did not.

Thirdly, the early laboratory sessions required perseverance from the teachers, as many students appeared unfamiliar with basic laboratory work. The question of what to include in the laboratory book was also ongoing, to the extent that this appeared to be holding back some groups from actually doing the experiment. Also, students did not engage with the 'symposium' part of the ISLE structure, being remarkably reluctant to talk to other groups about what they had done. Interestingly, this has not been remarked on in other ISLE studies. Possibly this is a cultural reluctance based on not wishing to appear inadequate ('whakama' in Maori), though this reluctance was exhibited by nearly all students regardless of ethnic background.

Finally, this course was initiated in the midst of significant changes within the School. This meant that one of the two academic teaching staff was assigned to the paper two months before its commencement date, creating a significant challenge in the course material preparation; and that laboratory equipment could only be acquired for seven out of the planned ten experiments.

Conclusions

We have demonstrated that the ISLE approach to the APhys111 paper has been successful in a small-class, non-physics-major New Zealand context. Students demonstrated conceptually-based learning outcomes, in particular laboratory skills. The much-reduced mathematical nature of the paper compared to traditional first-year physics and engineering papers did not hinder student understanding of physics concepts.

References

- Etkina, E., Murthy, S. & Zou, X. (2006). Using introductory labs to engage students in experimental design. *American Journal of Physics* 74(11), 979-986.
- Etkina, E. & Planinšič, G. (2014, March). Thinking like a scientist, *Physics World*.
- Etkina, E. & Van Heuvelen, A., (2007). Investigative Science Learning Environment - A Science Process Approach to Learning Physics. In: E. F. Redish and P. Cooney, (Eds.), *Research Based Reform of University Physics*, (AAPT).
- Etkina, E., Van Heuvelen, A., White-Brahmia, S., Brookes, D. T., Gentile, M., Murthy, S., Rosengrant, D., & Warren, A. (2006). Scientific abilities and their assessment. *Physical Review Special Topics – Physics Education Research* 2, 020103.
- Hake, R. R. Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. (1998). *American Journal of Physics* 66(1), 64-74.
- Hestenes, D., Wells, M. & Swackhamer, G. (1992). Force Concept Inventory. *The Physics Teacher*, 30, 141-158.
- Peter, M., Khoo, E., Cowie, B., Scott, J., & Round, H. (2017). *Reengineering an engineering course: How flipped classrooms afford transformative teaching, learning, and workplace competency*. Hamilton, New Zealand: University of Waikato.
- Poklinek Čančula, M., Planinšič, G. & Etkina, E. (2015). Analyzing patterns in experts' approaches to solving experimental problems. *American Journal of Physics*, 83(4), 366-374.
- Wage, K. E., Buck, J.R., Wright, C. H. G & Welch, T. B. (2005). The Signals and Systems Concept Inventory. *IEEE Transactions on Education*, 48(3), 448-461.