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Race to improve student understanding of uncertainty: Using LEGO race cars in the physics lab

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Laboratories using LEGO race cars were developed for students in an introductory physics topic with a high early drop-out rate. In a 2014 pilot study, the labs were offered to improve students’ confidence with experiments and laboratory skills, especially uncertainty propagation. This intervention was extended into the intro level physics topic the next year, for comparison and evaluation. Considering the pilot study, we subsequently adapted the delivery of the LEGO labs for a large Engineering Mechanics cohort. A qualitative survey of the students was taken to gain insight into their perception of the incorporation of LEGO race cars into physics labs. For Engineering, the findings show that LEGO physics was instrumental in teaching students the measurement and uncertainty, improving their lab reporting skills, and was a key factor in reducing the early attrition rate. This paper briefly recalls the results of the pilot study, and how variations in the delivery yielded better learning outcomes. A novel method is proposed for how LEGO race cars in a physics lab can help students increase their understanding of uncertainty and motivate them towards physics practicals, © 2018 American Association of Physics Teachers.

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I. INTRODUCTION

Laboratory sessions (labs) are an integral element of most undergraduate physics courses. The reasons for having them include: seeing things for “real,” learning through direct observation, connecting theory to practice, affirming and illustrating concepts, developing problem solving skills, gaining experimental skills, hands-on practical skills, acquiring data and an uncertainty analysis experience, report writing, and research skills development. However, none of these outcomes will necessarily be achieved simply through attending a laboratory class. The design of the laboratory session is critically important in delivering the lesson objectives and engaging students in the scientific process. A good laboratory session should help students understand the role of direct observation in physics and demonstrate the link between theory and practice through the outcomes of the experiments.

Laboratory skills are a key competency for students enrolling in Physics. The key findings of the study on the Australian higher education system recognized that around one-third of all the commencing students felt inadequately prepared for university. A study at the University of Adelaide analyzed the Australian literature and identified that there exists a real gap in students’ skills between high school and university, across a range of disciplines. In the case of Physics, students tend to have a perception of it before they experience it at first year University level. Physics is often considered one of the most challenging subjects to learn and contains difficult basic and traditional material of a mathematical nature. In particular, students who come from a non-physics background at secondary school level often find Physics laboratory work exceptionally challenging. We have noticed over several years that many of the students enrolled in an introductory level physics topic are often ignorant of the basic science skills allowing them to perform laboratory work.

It is well acknowledged in Physics (as it surely is in other disciplines) that one does not truly understand a concept until one can solve problems involving that concept. As a result, there is a heavy emphasis on problem solving in all Physics topics, including first year level topics. Indeed, there is a concern that many introductory physics courses do not help students develop the skills necessary to solve real problems in the context of physics. The results of an earlier study conducted by the University of Liverpool imply that students find some aspects of physics practical exercises interesting and others boring. According to this study, which surveyed year-10 students (n = 315) in the UK, the results highlighted the fact that while some students found topics on magnetism, nuclear energy, and cosmology to be interesting an equal number of students found the content on electricity, energy, forces, and mathematical aspects boring. Students’ reasons for finding physics practicals boring were gender-biased. A broader
carry out in first year university physics \((n = 207)\) at Monash University in Australia concluded that only 40% of students agreed that they enjoy the laboratory classes and fewer than half of the first year students found physics laboratory sessions fun. As a consequence, the American Association of Physics Teachers (AAPT) recommends that an early student experience with a stimulating scientific process can be a critical “turn-on” to physics.

Part of our role as teachers is to prepare students to be the scientists, engineers, and educators of the future. To do this effectively, we must help them develop a solid grounding in the skills of scientific practice. For instance, an understanding of measurement and uncertainty are fundamental to designing and conducting an experiment, and the subsequent interpretation of its findings. Experimentation and measurement lie at the heart of physics, and it is important that students develop an understanding of these concepts. However, the goal of measurement is often seen by these students almost exclusively acquiring a single “point” value for the quantity they are investigating, and not also realizing that there is measurement error and other aspects of variability which creates uncertainty in the point estimate. Lying at the heart of the problem is the great difficulty students have in translating the “words” of a problem into a “picture” of reality, where physical objects relate to each other through physical laws. We have to teach students that there is a degree of uncertainty associated with all data and that it is acceptable to be uncertain. Teaching these ideas, however, continues to be problematic.

Research shows that students struggle with understanding measurement and the nature of uncertainty. Yet conducting proper analysis of experimental uncertainty is a primary goal of introductory physics labs. Previous studies found that students leave introductory physics laboratory courses with an ability to carry out certain procedures, but lack a coherent understanding for the nature of uncertainty, irrespective of the student profile, or the way in which the laboratory course was delivered.

While in a laboratory, students are typically given instructions for calculating the mathematical constructs of uncertainty and are expected to absorb these ideas by following a recipe-based instructions provided through the lab manual. The findings of a study by Volkwyn suggest that introductory labs should be designed not only to teach those mathematical calculations used to quantify uncertainty, but to explicitly develop a conceptual understanding of uncertainty. Creating experiences that require students to build a conceptual understanding of measurement, perhaps before their ability to undertake the calculations, can be a solution. Thus, it is important to facilitate an introductory lab that enables students to understand uncertainty through interactive learning, to build lab skills through scientific investigation, and to engender positive attitudes toward physics.

Consistent with the AAPT recommendation that an early positive experience can set up a student for a productive longer-term relationship with physics, we set out to design an engaging, interactive, and fun first year introductory physics lab that introduced students to pivotal concepts in a real-world way. Using LEGO race cars enables a more student-centered approach to learning as opposed to a purely knowledge-focused teaching philosophy. A key concept of measurement is uncertainty in the measurement, and this can only properly be demonstrated to students by performing repeated measurements for an experiment. The use of LEGO race cars is one scenario that allows students to quickly perform their experiments repeatedly. This study investigates the understanding of the nature of uncertainty in physics in two different student cohorts, including an introductory physics cohort and an Engineering cohort, both before and after a LEGO lab experience. The research questions to evaluate the effectiveness of the LEGO lab experience were as follows:

1. What are the students’ response to a new LEGO lab as an inclusive and motivational tool in a physics course?
2. Does offering a LEGO lab as an introductory lab experience help in reducing the early attrition rate compared to a traditional lab?
3. Does the LEGO experience enhance student understanding of the nature of uncertainty, data collection, and data analysis?

The structure of the remainder of this paper is as follows. In Sec. II, we discuss our motivation for undertaking this study, while in Sec. III our methodology is outlined. In Sec. IV, the statistical analysis we employed is briefly discussed, with our results and a discussion of those results being given in Sec. V. Finally, in Sec. VI, some conclusions from this study are provided.

II. MOTIVATION

The motivation for implementing LEGO Physics in both intro-level physics and Engineering was based on the following observations:

1. We have an interesting and diverse population of students in our introductory level physics topic. Intro physics topics are comprised of students of different ages and backgrounds with vastly different previous scientific experience. For example, some have studied year-12 physics, but most have not. In fact, many of this student cohort were not enrolled in any traditional science course in senior high school, and as this is an introductory university course the students were not required to be. The university entrance requirement for South Australia is based on ATAR (Australian Tertiary Admission Ranking) scores, which themselves are based on a system to allow students to study a wide range of subject areas, but does not require that a science-based subject be undertaken. Thus, students enrolling into university courses, unless pre-requisites are specifically required by the university, do not have to complete a science based topic at the senior school level. A year-12 student is required to achieve 200 credits to be awarded the South Australian Certificate of Education (SACE). The specific requirements for high school students completing their SACE can be found on the SACE website.

2. For a number of years, we have been involved in the teaching of basic physics to first year students who have little to no prior knowledge of physics or mathematics. Those intro physics topics have been experiencing a very high early drop-out rate that we would specifically like to address. The large attrition rate can be attributed to a number of causes; however, one major factor is the difficulty the students have with very little prior relevant content knowledge to perform practicals. On analysis we found that some students would walk away from the topic after their first lab, which suggests a lack of basic science skills
to perform practicals may be a factor. We have also observed inexperience and uncertainty with regard to data collection, analysis, and report writing in some of the students who remained in the topic. Moreover, these students remained anxious about the laboratory experience. Always exploring different ways to minimise the early drop-out rate, the first author of this paper devised a LEGO Physics Lab.

(3) Prior research has been undertaken where a specific learning experience using robots was offered prior to the core components of the course. This study was designed to improve student’s self-assessment of their abilities in a first-year computer science course and it was found that students that rate their programming skill as average in comparison to their peers were most positively impacted. Robotics has served as a powerful educational tool in engineering to introduce students to real-world interdisciplinary applications, to build self-efficacy, and to stimulate their engagement. However, for students from a non-science background the difference between robots and standard lab equipment is less distinct. Comparatively, LEGO bricks are familiar to students from non-science backgrounds, and also quite “family friendly”; as such, every student is more comfortable with LEGO bricks than with typical physics lab equipment. Lack of self-efficacy or self-confidence was identified as one of the common factors that contribute to poor retention in STEM (Science, Technology, Engineering, and Mathematics). We introduced a novel approach that takes all the above mentioned factors into account. This approach allows students to experience a hands-on activity, using LEGO race cars and offered before their first traditional laboratory, with a view to improving their hands-on lab skills, their lab experience, and to give them confidence with uncertainty propagation calculations.

(4) In a study designed to reform the laboratory physics program for engineering students, it was found that the engineering staff in at least one large Australian university expected the introductory physics course to teach the basics of measurement and uncertainty to its engineering students. Apparently, this is the case at Flinders University as well.

III. METHOD

A. Pilot study—LEGO labs in intro level physics

At Flinders University, the introductory level course has a compulsory laboratory component. Each student is required to complete three formal traditional laboratories during the course, with each laboratory running for 3 h. These laboratory sessions were conducted by a Research Higher Degree (RHD) or Honors student in physics as the so-called demonstrator. The demonstrators are selected for each course from a common pool of RHD or Honors students who have undergone the same science demonstrator training. Four series of practical sessions were run in the initial semester, each with a different demonstrator from that pool. Note that from one year to the next this pool of demonstrators may change, for example, due to the RHD or Honors students completing their degrees. Usually the formal laboratories start in week 6 of the semester. The traditional laboratories were initially designed for students who had a physics background using physics laboratory equipment. As a consequence, in order to get a feel for how our non-physics cohort was progressing, the students are given a General Ability Test (Pre-Quiz) after 3 weeks of lectures. This quiz is used to determine the level of the students’ knowledge prior to entering the labs. It consists of ten questions covering both concepts and problem-solving aspects of the content. The General Ability Test (Pre-Quiz) was designed by the lead author; it is taken electronically and marked automatically with only a single attempt allowed.

The newly designed LEGO Physics labs ran in an intro-level physics topic in supplementary material S1, 2014. These labs allowed the students to experience a hands-on activity using LEGO race cars, before their first traditional laboratory, in order to improve their experience and develop confidence in the uncertainty propagation calculation. During that study, the students involved had come from a diverse range of backgrounds, but with no guaranteed knowledge of physics, or any science topic at all, either at the secondary or tertiary level. Thus, the goals of the LEGO labs were to provide students with a basic understanding of the scientific process, and more broadly with data and experimental analysis. Those experiments were designed to cover a range of topics, including the concept of uncertainty, the number of variables in an experiment, and the fairness of an experiment (i.e., whether the experiment, as designed, biased the result). The students also had the opportunity to provide their own suggestions into how the experiments could be modified and improved, so as to be able to draw a more robust conclusion from them.

The LEGO sessions were aimed at creating a familiar learning environment in order to support the students as they gained experience with less familiar techniques such as how to collect data, how to condense the information for presentation in a laboratory report, how to undertake a calculation of the uncertainties, and how to develop skills in recording work concisely and drawing conclusions based on the analyzed data. Each LEGO physics lab session consisted of 4 experiments and were offered in week 3 as the laboratory before their first formal practical. Those experiments were designed using a student-centered learning approach, which attempted to foster engagement by removing the anxiety associated with unfamiliar laboratory tasks. LEGO experiments were designed to give students the opportunities to present information in a laboratory report, calculate uncertainties, record work concisely, and to help them build skills in data evaluation and analysis. Students were invited to complete three experiments out of the four that were available, with submission of the completed reports required within 24 h of the allocated lab session. The demonstrators marked the lab reports and provided constructive feedback to students online via the course’s Learning Management System (Moodle) within a week of submission.

For each LEGO experiment, an introduction was provided, explaining the goals of the experiment, and some potential hypotheses related to the outcomes of the measurements were also given. The experiments were designed to cover different ideas and concepts involved in science and the students had to identify in the experiment which variable was being investigated and thus what conclusion could be drawn from the data collected. To assess the efficacy of the LEGO physics lab, the performance of the students in their first traditional laboratory was compared across the cohorts. The experiments as designed were as follows:

(1) Unleashing the Potential Energy

The students are provided with a racing area, a timer, and a LEGO race car with a pullback motor. The students measure the time taken for a car to travel a set distance,
when initially pulled back to different positions (thus providing the car with different amounts of energy). The students are asked to identify how far the car should be pulled back, and how different that variable should be between measurements. This experiment was designed to introduce the concept of variables and constants, as well as to guide the students in making realistic judgements of the experimental design. The distance the car travels during the measurement, including the start and end points, are determined by the students. The experiment is designed to help the students recognize that with the limitations of the equipment in use (such as a physical stopwatch), sufficient time and warning must be provided in the experiment to allow the timer to react, and thus to be able to provide meaningful results.

(2) **Ramping It Up**

The students are also provided with a ramp of variable height, with either a smooth, low-friction surface or a rough, high-friction surface, a timer, and a LEGO car. The students change the height of the ramp with respect to the base, measuring the height, angle, and time for the car to reach the base of the ramp. The students are asked to identify if there is a trend to the speed of the car, and to determine why the trend occurs. The students were also asked to identify any outside factors that might be affecting this experiment, and identifying gravity as the source of the acceleration experienced by the vehicle.

(3) **A Fraction Too Much/Little Friction**

During this experiment, the students repeat the procedure from “Ramping It Up,” but now employing a ramp of either greater or lesser friction. The students are then asked to consider these results in comparison with their previous results, and to identify the source of the change. The students are further asked to consider why the height of the ramp during the two experiments was kept the same, and why the same LEGO vehicle must be used for each experiment. This investigation seeks to help students realize why outside factors, those that may not usually be considered (such as friction), play an important part in the understanding and interpretation of results.

(4) **Do Red Cars Go Faster?**

The students are here provided with a racing area, a stopwatch and two cars of different design, one red and one blue. They are also provided with enough sets of wheels, such that each car can be fitted with the same wheels if desired. The students are asked to measure the time taken for the cars to travel a set distance, and thus determine if the average speed of the red car is greater than that of the blue car (or vice versa). The students are next asked to identify if one car did travel faster than the other, and could that be attributed to the cars’ color, and why they think this is or is not the case. They are encouraged to consider their answer in terms of the design of the cars, including their shape, wheels, weight, and height above the racing floor. The students are then asked to draw conclusions as to the validity of the experiment, and to suggest modifications to the experiment so as to make it fairer.

In each of the experimental tasks fundamental concepts are introduced, including the various formulae for speed, velocity and acceleration, potential and kinetic energy, as well as the calculation of the track angles. Further, uncertainty analysis is introduced and explained for each experiment, with the students being required to identify the sources of the uncertainty (and if it can be determined, the magnitude) and for the quantifiable sources, and then propagate that uncertainty to the final result. For each experiment, the students are asked to discuss the limitations and drawbacks of the experiment, and suggest improvements. Students subsequently need to submit a lab report for assessment.

We extended this approach to a 2015 intro-level physics topic and an Engineering Mechanics topic, for a comparative study and to determine if we can convey the nature of uncertainty to those students through a simple LEGO physics approach. For the 2015 study, the participation in the LEGO lab was compulsory for both the Engineering and intro-level physics students, whereas for the 2014 pilot it was optional. In 2014 we did not offer a LEGO lab for our engineering cohort, so we used the 2014 traditional lab (Practical 1) score for both cohorts to represent a controlled study. We linked the first quiz offered in week 2 of the semester, for the intro-level physics topic in both years 2014 and 2015, as a general ability test to assess the students in terms of their individual strengths and weaknesses. We collected data using two different methods to understand and collate students’ responses to a new LEGO lab experience. For the intro-level physics topics informed observational data and feedback were gathered while students were carrying out their LEGO lab, whereas for the Engineering topic, a formal class survey was administrated.

### B. LEGO labs in engineering

Reflecting on the outcomes of the pilot study (see Sec. V), the first author made some adaptations to the delivery of the LEGO labs for the large Engineering cohort offered in supplemental material S2, 2015, where initially students in the LEGO labs for the intro physics topic worked in groups of 5, in the subsequent design only pairs were allowed. The lecturer made the grouping uniform throughout all labs, and instructed the lab demonstrators to make sure the students conducted all activities rather than giving them an option to select three out of the four given activities. The same proportion of marks was given for all labs including the LEGO lab. For the pilot study, the weight of the LEGO lab was 5% towards the students’ overall topic grade compared to a 20% lab component for this topic. This was also the case in the Engineering topic. Students were required to submit their e-lab report individually. As will become apparent later, these adaptations yielded the desired learning outcomes. All the engineering students were invited to complete a four-point Likert scale survey on the completion of their lab session. A paper and pencil class survey was administered during the 12 lab sessions we ran for this topic. We have utilized a slightly modified version of the validated survey instrument developed by Vasan et al., here consisting of nine statements that they could agree or disagree with a scale of 0 (strongly disagree) to 3 (strongly agree). This is a validated survey instrument used by several medical education researchers. The statements in question are shown in Table II. The modified survey also consisted of two open-ended questions as follows:

1. Which aspects of the LEGO classes were most valuable to your learning?
2. What skills have you learned from this LEGO session?
Table I. Summary of the admissions data for the introductory physics topic. Only those students who ultimately completed the topic were included in this table.

<table>
<thead>
<tr>
<th>Basis of Admissiona</th>
<th>2014 (n = 67) (%)</th>
<th>2015 (n = 56) (%)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher education course</td>
<td>15 13</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Mature age (&gt;23)</td>
<td>8 23</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Year 11/12</td>
<td>40 20</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>TAFE award</td>
<td>9 14</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>Non commencing student</td>
<td>22 29</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>7 1</td>
<td>0.10</td>
<td></td>
</tr>
</tbody>
</table>

aHigher Education Course = Australian or overseas equivalent (complete/incomplete); Mature Age = Special entry provisions related to age; Year 11/12 = Secondary education undertaken at school; TAFE = Technical and Further Education; Other = Other basis.

IV. STATISTICAL ANALYSIS

We use histograms and box plots to illustrate the distribution of scores in each laboratory class (the three traditional physics labs) for each year. Data are described using mean ± SD for continuous variables and percentage for categorical variables such as admission data. The number of students in the cohort in a given year is defined by n. Note that n can vary depending on whether we are considering the lab classes or the student enrollment in the topic in question, as not every student in the topic necessarily undertook the lab component. Most did, but in a given year some lab exemptions were permitted.

Differences in the basis of admission for students between years were compared using a binomial test of proportions for each category of admission. Correlations between general ability and practical scores were assessed using Pearson’s r coefficient of correlation. Mean scores across years for each practical or lab were compared using independent t-tests. A value of p < 0.05 was considered as being statistically significant.

V. RESULTS

A. Pilot study

1. Student characteristics

Table I describes the overall characteristics of the students in the two intro level cohorts. Students are admitted based on a code that identifies the main criterion used by the Higher Education Provider in granting admission to the current course. Students enroll in a course or unit of study (intro level physics topic here) from different categories given in Table I (a description of these categories is given in the footnote of the table). A student is considered to be a commencing student if she/he has enrolled in the course for the first time, at the higher education provider, or an antecedent higher education provider between 1 January of the Collection Year and 31 December of the Collection Year. Non-commencing or continuing students comprise all the other students.

There was a significantly higher percentage of mature age students (23% versus 8%, p < 0.05) and a significantly lower percentage of students that had completed year 11/12 (20% versus 40%, p < 0.05) in 2015 compared to 2014. These differences in the makeup of the two cohorts (between 2014 and 2015) will invariably present some challenges in interpreting the analysis results for the two years.

2. Student responses of the LEGO lab

The processes of observing phenomena, recording data, and analyzing the data, afforded students a unique opportunity to relate a familiar, concrete experience to the scientific method. Students reported that the LEGO lab sessions eased their anxiety prior to the first formal laboratory session, and provided valuable preparation through collaborative learning. Students reported that knowing how to prepare laboratory reports and objectively evaluate the laboratory results were the best aspects of the LEGO session. Comments received for the best aspects of LEGO labs include: “The session was quite enjoyable and educational”; “Knowing how to complete lab reports and objectively evaluate results of labs”; “I like fun/friendship/teamwork”; “the fun factor was most valuable”; and “I like LEGO.” The student feedback suggested that the LEGO sessions eased students’ anxiety prior to the first formal laboratory session, providing valuable preparation.

3. Retention

All the students that attended the LEGO lab sessions in 2014 stayed on in the topic, indicating that this initiative has positively impacted student retention. Initially offered as an optional activity in Semester 1, 2014, only 30% of the class attended, two of whom were already high achievers. In 2015, we delivered the lab as a compulsory practical in order to

Table II. Survey results for the engineering cohort; of the 205 enrolled students 48 responded to the survey.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Percentage of strongly agree</th>
<th>Percentage of agree</th>
<th>Median score</th>
</tr>
</thead>
<tbody>
<tr>
<td>The LEGO lab instructions were clear.</td>
<td>69</td>
<td>29</td>
<td>3</td>
</tr>
<tr>
<td>The LEGO physics was enjoyable.</td>
<td>77</td>
<td>23</td>
<td>3</td>
</tr>
<tr>
<td>Experimental work makes physics more enjoyable for me.</td>
<td>86</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>I learned new practical skills after participating in LEGO Physics class.</td>
<td>33</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>It is helpful to understand assumptions that go into making predictions.</td>
<td>69</td>
<td>31</td>
<td>3</td>
</tr>
<tr>
<td>As a result of LEGO class, I am more interested in Practicals.</td>
<td>61</td>
<td>38</td>
<td>3</td>
</tr>
<tr>
<td>As a result of LEGO class, I am confident in measuring physical quantities with appropriate accuracy.</td>
<td>50</td>
<td>48</td>
<td>3</td>
</tr>
<tr>
<td>As a result of LEGO class, I am able to recognize factors that could affect the reliability of their measurements.</td>
<td>75</td>
<td>23</td>
<td>3</td>
</tr>
<tr>
<td>The LEGO class was a valuable part of this topic.</td>
<td>63</td>
<td>35</td>
<td>3</td>
</tr>
</tbody>
</table>

aScores rated on a four-point Likert scale (0 = strongly disagree, 3 = strongly agree).
better analyze student learning data. The evaluation of the findings for the implementation of LEGO lab in the intro level topic in supplementary material S1 2015 show that the early-attrition rate is stabilizing at a lower rate than previously observed (early attrition rate was 11% in 2015 compared to 13.5% in 2014). Furthermore, we noted that the early attrition rate for this topic was 28.5% in year 2013 when the LEGO lab was not delivered. While other factors may have played a part in this improvement, it seems likely that the LEGO lab initiative has positively impacted student retention. In 2013, this topic was delivered in the current format for the first time, so indeed other improvements were also made. For example, in 2014, the topic content was delivered in a better order and laboratory sessions were more in phase with the lectures.

The responses to a four-point Likert scale survey on the classes show that the students enjoyed their LEGO lab experience. On a positive note, we have not seen any students dropping out just based on their first traditional, non-LEGO laboratory experience, which did happen in 2013. To that extent, along with the documented early-attrition rates, we can say that our LEGO lab has been a factor in improving student retention.

4. Comparison of lab scores and final grades for 2014 versus 2015

Figure 1 shows the distribution of scores for the formal lab practical 1, which immediately followed the LEGO lab in 2014 and 2015. There was an apparent reduction in the mean scores between the years (7.18 ± 1.44 versus 5.88 ± 1.61, p < 0.001). Note that the 2014 data only included those who attended the LEGO session. Figure 2 depicts the distribution of scores in each year (2014 and 2015) by class (formal lab practical) following the LEGO lab, in more detail. The graph in Fig. 2 is a standard box and whiskers plot showing the median, inter-quartile range, and whiskers to represent the bulk of the data. The boxes represent the inter-quartile range (IQR) (i.e., 25th to 75th percentile) and the “whiskers” beyond the boxes represent the upper and lower adjacent values as defined by Tukey (i.e., a distance of 1.5× the IQR). Finally, the dots represent any (outlier) values outside of these limits. Across the three practical labs there was also a decline in scores for the students’ lab-reporting skills (7.44 ± 1.50 versus 6.37 ± 1.74, p < 0.001) between 2014 and 2015 (see Fig. 2). However, when the uncertainty (SD) is taken into account on all the calculated means there is in fact little difference between the three lab classes within each year. This suggests that the conclusions made by Parappilly et al., when assessing the learning outcomes of intro level physics labs used in conjunction with LEGO physics, quite likely remain valid. The difficulties in making a multi-year assessment for the utility of LEGO physics, as foreshadowed in part earlier, include the very different backgrounds of the intro cohorts in 2014 and 2015 (see Table I), and perhaps more importantly that the teaching teams, in particular, the lab demonstrators, were different in 2014 and 2015. This can become problematic when, in terms of assessment, the expectations of the demonstrators vary between one year and the next, owing to their different levels of experience in demonstrating laboratories and in marking formal practical assessments.

Figure 3 displays the correlations between general ability scores, as measured by the General Ability Test (Pre-Quiz), and Practical 1 Lab scores for 2014 and 2015. There was some correlation between the scores in 2014 (Pearson’s r = 0.28, p = 0.03) but not in 2015 (r = 0.07, p = 0.67). The correlations, although quite significant for the first year (2014) are still relatively weak and show that the Pre-Quiz ability cannot explain the subsequent score for the practicals. Figure 3 thus shows that there was only a relative weak correlation between the (Pre-Quiz) score and Practical 1 Lab scores, indicating that the two assessments are clearly gauging different competencies. We found some difficulty in quantitatively comparing the learning outcomes due to differences in the backgrounds of the student cohorts in the different years, specifically more mature age students with lower overall ability in 2015 compared to 2014. In addition, different lab demonstrators in the two years also made formal comparisons difficult. Given these caveats, the 2015 results do not invalidate those from the 2014 pilot study.
Finally, Fig. 4 shows the frequency distribution of the cohort final grades in 2014 compared to those in 2015. There was a significant change in the grades, with fewer Distinction/High Distinction’s and more Passes in 2015 versus what was found in 2014 ($\chi^2 = 7.92$, df = 3, and $p = 0.048$). The grades are defined as follows:

- **High Distinction (HD):** An outstanding performance; mark range 85%–100%. Indicating the student has a high level of understanding across the entire content of the course, shown considerable additional work in wider areas relevant to the topic, and has demonstrated the acquisition of an advanced level of knowledge required for meeting topic objectives and passing the range of topic elements at the highest level.
- **Distinction (DN):** A superior performance; mark range 75%–84%. Indicates that the student has undertaken all of the required core work for the topic at a high level and considerable additional work in wider areas relevant to the topic. Has demonstrated advanced knowledge required for meeting topic objectives and completing assessment exercises at a high standard.
- **Credit (CR):** A good performance; mark range 65%–74%. Indicates that the student has undertaken all of the required core work for the topic and additional work in wider areas relevant to the topic, and has demonstrated a sound level of knowledge required for meeting topic objectives and completing assessment exercises at a proficient standard.
- **Pass (P):** An acceptable level of performance; mark range 50%–64%. Indicates that the student has undertaken the required core work for the topic and has demonstrated at least an adequate level of knowledge required for meeting topic objectives and satisfactorily completing essential assessment exercises.
- **Fail (F):** Unsatisfactory performance, below the minimum expected level; mark range 0%–49%. Indicates that student has failed to complete essential topic elements or required assessment tasks at an acceptable level, in accordance with topic objectives.

### B. LEGO labs in engineering

#### 1. Engineering course cohort: Student’s responses to the LEGO experience

The survey was intended to explore students’ views of the LEGO lab experience and to understand if the LEGO lab helped students to develop some practical skills. For the engineering cohort, 48 students (out of 205 enrolled) responded to the survey; Table II summarizes the responses to the nine statements. All the responding engineering students were in agreement (100%) with statements 2 and 3, namely, that experimental work makes Physics more enjoyable for them and that attending the LEGO lab helped them to understand the assumptions that go into making predictions. These findings are consistent with the previous literature results that laboratory work can increase students’ motivation. Thus, an introductory LEGO lab can potentially act as a powerful motivational tool to keep students studying physics. In addition, 98% of the students felt that after attending the LEGO lab session they became confident in measuring physical quantities, with appropriate accuracy, and that they were able to recognize factors that could affect the reliability of their measurements. The students’ responses to the survey likely confirm that LEGO lab fostered a positive attitude in the students towards practicals, and are in agreement with the study results of Ref. 6. This is also in agreement with previous results that practical work can improve students’ understanding of science and promote their conceptual development by allowing them to “visualize” the laws and theories of science. In response to statement 4, about whether they learned new practical skills after participating in a LEGO Physics class, only 17% of the students disagreed with that statement.

The processes of observing phenomena, recording data, and analyzing the data to enable explanation of the observations afforded students a unique opportunity to relate a familiar, concrete experience to the scientific method. Designed activities helped them to develop lab skills through improved understanding of scientific literacy and time management. Data from the survey illustrated the range of responses given by students for the open-ended questions. The engineering students expressed their skill development in completing the LEGO lab with comments such as: “Being able to...
quantitatively record our results is the best aspect of LEGO”;
“I learnt about the importance of accuracy in measurements”;
“Seeing concepts we’ve learnt in real-life”;
“Enhanced my skills in effective predictions, assumptions and measurement”;
“Thinking about how the experiments were structured”; “Seeing the physical side of the theory”;
“Learning uncertainty is the best aspect”; “Multi-tasking” and so on. Note that these comments were not “cherry picked”; they provide a balanced sample of the responses received from this cohort.

2. Improved student learning

Figure 5 shows the engineering topic Practical 1 Scores (out of 10) after a traditional lab for year 2014 ($n = 63$) and a LEGO lab prior to the traditional lab in 2015 ($n = 148$). We reiterate that the LEGO labs were not offered for the 2014 Engineering cohort. The figure shows that there was a clear increase in the mean ($\pm$SD) scores in 2015 compared to 2014 ($8.0 \pm 1.2$ versus $6.37 \pm 1.74$, $p < 0.001$), although when the uncertainties on the mean are considered we accept we need to be a little circumspect with our claims. These results are in agreement with previous research demonstrating that thorough preparation before a lab session improves students’ performance in the lab and that follow-up work can lead to meaningful learning. In addition, there is preliminary data to show that the LEGO lab can help retain students, as was demonstrated by a reduced attrition rate of 28% recorded in 2015 compared to a 38% attrition in 2014 for the Engineering topic.

Nonetheless, the revised model of delivery of the LEGO labs indicated that they have the potential to teach students uncertainty in an informal lab setting. The engineering students clearly benefited from them, as can be either gleaned from the responses in Table II or the results embodied in Fig. 5. These labs can also be used in the intro level physics topic in years 2014 ($n = 63$) and after completing an initial LEGO lab in 2015 ($n = 148$). Mean ($\pm$SD) scores for 2014 were clearly higher in 2015 compared to 2014 ($8.0 \pm 1.2$ versus $6.37 \pm 1.74$, $p < 0.001$).

VI. CONCLUSIONS

This study examined the effects of LEGO labs on two different student cohorts. Although the LEGO approach was clearly successful in improving students’ understanding of uncertainty and data collection (compared to the traditional laboratory), for the Engineering cohort the situation was less clear cut. We believe this difficulty was caused by the very different backgrounds of the cohorts in intro-physics in 2015 compared to 2014 and by the different lab demonstrators we employed in 2015 compared to 2014. One very clear lesson from the present study was that in any multi-year investigation the same teaching team, in particular the lab demonstrators, should be retained. Nonetheless, the present intro-physics investigation largely confirmed the results from the pilot study of Parappilly et al.,24 in that LEGO labs also provided positive learning experience for the intro-physics students. Both cohorts reported the LEGO lab to be enjoyable and increased their interest in the practical components of the course. Our results show that by creating lab experiences such as a LEGO lab, one can solve the traditional problem of helping students comprehend the quite abstract concept of uncertainty. In addition, the LEGO lab can be a factor in the reduction of early attrition rates, as supported by the data obtained for both the Intro and Engineering topics.

Roll-out at interstate universities is currently in progress. Beyond the higher education arena, some South Australian high schools have adopted our LEGO Physics approach in an effort to excite and engage their students in the subject. The impact of the LEGO physics approach is further demonstrated through our engagement with a collaborative Phonelab venture. School students are being taught real-time data collection using Live-Trackers and LEGO race cars, thus allowing them to learn Physics terminology in non-scientific language and in terms they understand, rather than as complicated scientific variables. A new and exciting direction for this research is in our implementation of Phonelabs at both Flinders University and our collaborator universities as an intervention to measure changes in students’ Physics knowledge and skills through a multi-year, multi-instructor, and multi-institutional evaluation.

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![Fig. 5. Box plot showing Practical 1 Scores (out of 10) for the Engineering topic in years 2014 ($n = 63$) and after completing an initial LEGO lab in 2015 ($n = 148$). Mean ($\pm$SD) scores for 2014 were clearly higher in 2015 compared to 2014 ($8.0 \pm 1.2$ versus $6.37 \pm 1.74$, $p < 0.001$).](image-url)