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Transforming the Learning Environment of Undergraduate Physics Laboratories to Enhance Physics Inquiry Processes

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Abstract

Concerns persist regarding the lack of promotion of students' scientific inquiry processes in undergraduate physics laboratories. The consensus in the literature is that, especially in the early years of undergraduate physics programs, students' laboratory work is characterized by recipe type, step-by-step instructions for activities where the aim is often confirmation of an already well-established physics principle or concept. In response to evidence reflecting these concerns at their university, the authors successfully secured funding for this study. A mixed-method design was employed. In the 2011/2012 academic year baseline data were collected. A quantitative survey, the Undergraduate Physics Laboratory Learning Environment Scale (UPLLES) was developed, validated, and used to explore students' perceptions of their physics laboratory environments. Analysis of data from the UPLLES and from interviews confirmed the concerns evident in the literature and in a previous evaluation of laboratories undertaken in 2002. To address these concerns the activities that students were to perform in the laboratory section of the course/s were re/designed to engage students in more inquiry oriented thinking and activity. In Fall 2012, the newly developed laboratory activities and tutorials, were implemented for the first time in PHYS124; a first year course. These changes were accompanied by structured training of teaching assistants and changes to the structure of the evaluation of students' laboratory performance. At the end of that term the UPLLES was administered ($n = 266$) and interviews with students conducted ($n = 16$) to explore their perceptions of their laboratory environments. Statistically significant differences ($p < .001$) between the students in the PHYS 124 classes of 2011/2012 and 2012/2013 across all dimensions were found. Effect sizes of 0.82 to 1.3, between the views of students in the first semester physics classes of 2011/2012 and 2012/2013, were also calculated suggesting positive changes in the laboratory inquiry orientation. In their interviews, students confirmed and detailed these positive changes while still noting areas for future improvement.

Key words: undergraduate physics education, inquiry, laboratory learning environments.

Introduction: The problem facing us at the University of Alberta

Undergraduate science laboratories are major teaching components within university science faculties worldwide. In the Department of Physics at the University of Alberta the annual budget for undergraduate laboratories is approximately \$1.6M for teaching assistants' (TAs) and staff salaries, and space is allocated within the new Centennial Centre for Interdisciplinary Science with a capital cost of over \$13M. Equipment maintenance adds around \$50 000 per annum. Annually, over 2 000 undergraduate students pass through these laboratories. The cost, effort, and time involved are considerable. Obviously, laboratories are a key element of the undergraduate physics learning experience at the University of Alberta. This situation is the same at many universities, worldwide.

However, despite their importance, the quality and extent of student inquiry in first-year undergraduate Physics laboratories is a long-standing issue across universities in Canada and internationally. This, in part, is due to diverse opinions regarding the purpose/s of such activities, ranging from the development of critical thinking skills to equipment manipulation. Key objectives reportedly range from 'developing critical thinking skills' to 'glassware manipulation' (Weaver et al., 2008). Many students believe the primary objective of labs is to "reinforce the lecture material" (Russell et al., 2008), developing a 'confirmation' expectation through their high school experiences (Weaver et al., 2008). Recipe-like laboratory formats persist as the dominant element of instructional design, but these formats do not adequately support the development of students' inquiry processes. To determine the objective of labs, the National Research Council commissioned a detailed investigation (National Academy of Sciences, 1996), asking what the primary motivation of the undergraduate laboratory should be. Contrary to most traditional views, it is increasingly acknowledged that *'science as inquiry'* should pedagogically guide laboratory-based instruction (National Academy of Sciences, 1996), and that labs should engage students in thinking processes and activities similar to practicing scientists (National Research Council, 2000).

At high-school and undergraduate levels, many teachers and students believe, that science advances linearly, following the 'hypothesis-testing model' (Windschitl, 2002). In classrooms this is called *the scientific method*. This view is an inadequate representation of scientific inquiry and reasoning. Many scientific advances have been made without following this so-called method. Sometimes scientists have no hypothesis. Other times, discoveries are made serendipitously. It would be a challenge to find evidence of a linear 'scientific method' in much of advanced physics research, not to mention in many great scientific advances of the past century. Contemporary education literature suggests that a universal scientific method does not exist at all, and that inquiry proceeds in many, varied ways (Alters, 1997; Knorr-Cetina, 1999; McGinn & Roth, 1999). Importantly, recent literature also strongly advocates an *inquiry-based approach* to laboratory pedagogy and learning. Inquiry-oriented laboratories stimulate learners to develop increased independence and are more epistemologically and practically aligned to authentic science. Students focus on independently devising experimental methods and arriving at reasoned findings. Inquiry-based labs can enhance subject understanding and foster positive attitudes toward science and science learning (Chang & Mao, 1999; Luckie et al., 2004). The position in this paper is in accord with that of the

NRC and other contemporary science education literature; that the development of student's inquiry processes is of primary importance in university level science laboratories.

A clear indication that the undergraduate Physics labs may not be adequately challenging students to become independent, inquiry oriented thinkers came in 2002 in a report (Beamish et al., 2002) to the curriculum committee of the Department of Physics from a team led by Beamish, a co-author of this paper. The committee's findings were worrying. Students were, "uniformly negative about their overall laboratory experience, despite liking the hands-on aspects of the lab, the opportunity to work in groups, and their TAs". First year students were especially critical. Only 3 of 240 students considered the lab component of the course excellent. In PHYS 124, the largest first-year physics course with over 1 000 registered students in 2011, 73 out of 87 students rated the lab component at 3 or lower on a 5-point scale. Only 14 out of 87 students found the labs interesting and stimulating. The report proposed that "significant changes" were needed.

From a perusal of the 2011/2012 PHYS 124 laboratory manual it was obvious that the labs were almost entirely confirmatory in orientation and therefore unsatisfactory as authentic physics inquiry learning experiences. For each lab, students received a set of instructions that they were expected to follow closely. There was little stimulus or opportunity for independent thought, and little authentic inquiry. Other problematic issues were also evident regarding the operation of these laboratories. Firstly, the laboratories and the lectures were not well sequenced, with the material being introduced in lectures sometimes weeks after the related lab. Secondly, there was no interaction between the class lecturer and the laboratories. Finally, there was a vast difference in teaching ability and performance of the TAs in different lab sections. Therefore, the situation as it existed was contrary to and unsupportive of inquiry-based approaches that have been shown to foster creativity, interest, enhanced understanding and positive attitudes. Our funded project aimed to begin to address these issues.

The team building process and member roles

The second and third authors of this paper are both Professors within the Physics Department at the University of Alberta, and are closely involved in teaching within the Department. Both were highly interested and invested in addressing the issues raised in the earlier evaluation/s of the first-year physics laboratories. In November 2010 they approached the first author to ascertain his interest in being involved in the project primarily as an evaluator of the curricular and pedagogical changes that they envisioned. Together, the three authors submitted a funding proposal that was successful.

There was a quite clear distinction in the roles of the authors and such role differentiation contributed to the overall smooth operation of the project. Authors 2 and 3 led the development of the new laboratory curriculum including the activities and tutorials, liaised between the non-academic members of the Physics Department responsible for day-to-day laboratory management, engaged in the training of the TAs regarding the new laboratory activities and tutorials, and organized access to students for the first author. The first author took responsibility for conducting the evaluation of the changes to date. It enabled the Physics Department members to initiate changes to their program and pedagogies, and the external evaluator from the Education Faculty to undertake the evaluation research in an ethical manner that did not compromise the anonymity or confidentiality of the students who provided feedback on those changes.

The proposed solution: the plan and its enactment

The extent to which laboratories are inquiry-oriented laboratories varies along a continuum. At one end of the continuum is the 'confirmation,' recipe-like or method-based lab, within which students have limited responsibility for independent thought or inquiry. At the other end are 'research apprenticeships' within which students, typically post-graduates, are expected to show evidence of considerable independent thought and inquiry as they progress to answer a question that they themselves pose using methods they devise (Windschitl, 2002). This level most closely resembles authentic scientific research. Located between these ends of the continuum are *'guided inquiry'* laboratories. Here, the procedures to solve a problem are decided upon by the student, who receives partial guidance from the instructor. They represent a balanced pedagogical approach for first-year undergraduate laboratories that are populated mainly by students whose experiences are grounded in high school, confirmatory-type studies. *'Guided inquiry'* labs can promote independence and creativity and provide support and intellectual scaffolding for students from instructors.

The team received funding support to introduce A *guided inquiry* based teaching and learning in the first-year physics labs at the University of Alberta. Guided inquiry meant that the students were not to be left to flounder in a 'sink or swim' environment when engaging with the new activities. Rather, they were to be supported by the TAs whose role it was to scaffold their thinking and provide guidance. The implementation of such a philosophy to the laboratories brought with it challenges. There was considerable variation in teaching skill amongst our TAs; we faced highly questionable conditioning and preparation in many students coming out of high school; and it was anticipated that instructors and TAs would encounter the need to address different pedagogical issues than they would in more traditional, 'confirmatory' labs. Inquiry-based learning implies significant changes to existing methods and it was imperative to increase the pedagogical awareness and capabilities of our instructors and TAs.

To begin to address these issues, TA meetings were conducted every Friday at 2PM for the following week's lab. Each meeting lasted about an hour. These meetings were made mandatory for all TAs whereas, in the past, they were optional. The purpose of the meetings was to discuss the pedagogical objectives of the following week's labs, ensure the TAs were familiarized with the equipment to be used, and to discuss any issues or comments the TAs had about the lab that had been completed during the week of the meeting. Suggestions for improvements, for example, to marking, or means to enhance efficiencies were encouraged and often discussed. Four-to-five slide PowerPoint presentations for the TAs regarding forthcoming laboratory and tutorial activities were developed by the instructors, shown at the meeting, and emailed to all TAs for their information and use. The TAs were permitted to make modifications as they saw fit according to their individual teaching styles.

In determining which activities were to be conducted by students in the laboratories the key criteria was that the labs and tutorials needed to be based in engagement in guided inquiry, and not on rote, recipe-following as in the past. The activities needed to link to modern work in physics as much as realistically possible given the low level (first year). They needed to be able to accommodate students who varied considerably in their previous access to and/or experience conducting physics experiments in high school. They needed to avoid 'magic formulas' that the students simply had to be told, without any understanding of where they come from, which was a significant issue in the previous lab format. The question that was to be put to students in the laboratory and tutorial activities was to be, "How, do I solve the problem?" rather than "What is the final answer?" The activities also needed to continually reinforce students' data presentation and data-handling skills, and encourage students' independence though the use of their own portable computers as much as possible, even though lab computers were provided for those needing them. A key variation between 2011/2012 and 2012/2013 classes was that students in the 2012/2013 classes were allowed to take their data and complete their laboratory reports after the lab session had concluded. This was in contrast to previous practice in which they were expected to complete their lab reports prior to leaving the laboratory session.

Tutorials were added to the laboratory schedule, replacing some experimental sessions, with the main intention to provide a source of questions or problems that would be relevant to modern happenings in the field of physics. These were intended to capture the students' imagination, while providing challenging material for independent thought. Additionally, they were meant to push the students' computational and data-handling skills. For example, one tutorial included calculations about the transits of Venus, the most recent transit occurring to great fanfare in 2012, only a few months prior to the tutorial. Another asked students to download images of the Sun from the week prior to their tutorial, taken by NASA's SOHO satellite, and to use the images to calculate the Sun's rotation rate. Therefore, the tutorials offered a flexibility that a lab could not always offer, especially with regards current happening in the physics 'world'. The eventual aim is for future instructors to invent one or two new tutorials each semester, to be added to a collection of such activities for future use and reference. Over the course of the 2012/2013 fall term students engaged in 4 tutorials and 6 laboratory activities, compared with 10 laboratory activities and no tutorials in the previous year and for several years before.

The evaluation of the changes made

A mixed-method methodology was selected for the evaluation of this project and the effect of the curricular and pedagogical changes. Mixed-methods research is a pragmatic approach to research that allows researchers to "select methods and approaches with respect to their underlying research questions, rather than with regard to some preconceived biases about which research paradigm should have hegemony in social science research" (Johnson & Onwuegbuzie, 2004). This evaluation involved the development and use of a learning environment survey, custom-oriented to undergraduate physics laboratories (Thomas, Meldrum & Beamish, 2013), and interviews. A 23-item instrument, the UPLLES (Undergraduate Physics Laboratory Learning Environment Survey) was developed and validated through (a) factor analysis, using responses of 476 students, and (b) semi-structured interviews with 19 of those students (Thomas, Meldrum & Beamish, 2013). The five sub-scales of the UPLLES are Inquiry Orientation (5 items), Integration (5 items), Material Environment (4 items), Student Community (6 items), and Instructor Support (3 items). Each item on the instrument is scored on a 5-point Likert scale (1 = Almost Never to 5 = Almost Always). Table 1 (Thomas, Meldrum & Beamish, 2013) is a description of each of the five subscales and the learning environment dimensions they represent. Table 2 shows the item-mean values (Min = 1, Max = 5), Cronbach's alpha values, and effect sizes for each of the sub-scales, pre- (2011/2012, $N = 269$) and post-change (2012/2013, $N = 265$).

Table 1: Description of scales and a sample item for each scale on the UPLLES

Scale Name	Description (Extent to which students consider:)	Sample item (In my physics laboratory classes:)
Integration	…that laboratory activities and content are integrated with non-laboratory & theory classes.	…students understand the relevance of what they are learning in their physics lectures.
Student Community	…that students are helpful and supportive of each other and their physics learning.	…students carefully consider the ideas of others in the class.
Inquiry Orientation	…they are asked to engage in inquiry-type investigations and thinking to learn about physics.	…students design their own ways of investigating problems.
Instructor Support	…they are supported and encouraged by laboratory instructors to engage in and improve their physics learning.	…instructors encourage students to think about how to improve their lab performance.
Material Environment	…that the material resources in the physics laboratories are adequate for the performance of the required tasks.	…the materials that students need are readily available.

The UPLLES was used, with interviews, to evaluate the 2011/2012 first-year Physics laboratory environments at the University of Alberta, i.e., pre-pedagogical change.

Table 2: Pre- and post- item mean scores, cronbach alphas and effect sizes for PHYS 124 students' responses to UPLLES classroom environment scale

		Inquiry Orientation	Integration	Material Environment	Student Community	Instructor Support
Pre (2011/2012)	Mean	2.410	3.155	3.725	3.641	2.870
	S.D.	0.749	0.909	0.743	0.733	0.983
	α	0.75	0.76	0.66	0.84	0.71
Post (2012/2013)	Mean	3.379*	4.005*	4.316*	4.135*	3.627*
	S.D.	0.739	0.696	0.541	0.589	0.871
	α	0.77	0.85	0.62	0.80	0.75
	Effect size	1.30	1.05	0.85	1.19	0.82

*$p < .001$

The data analysis confirmed their lack of inquiry orientation. Table 2 shows the pre-pedagogical statistical findings. In summarizing the interviews, students confirmed the 'recipe-like' format of the experiments; "Mostly, we just follow the procedure in the lab manual... much like high school physics, still... we don't get to design anything on our own," and "when you are doing the experiment it's like a step-by-step of what you are supposed to do so that you get close enough to the proper results". They bemoaned the intense nature of the lab experience and the pressure on them to complete all work in three hours; "You were just focusing on rushing and writing up the conclusion as quickly as you can and you're not really thinking about the science behind it", and "The labs are kinda rushed... they don't let you completely immerse yourself in the experience that you are having." Further, they criticized the lack of connection and integration between the lectures and the lab component; "The labs are quite a bit ahead of the class. So sometimes we'll be doing something in the lab and we haven't even touched (it) in class... we were doing waves for the last couple of labs and in class we just started on labs" and "There was a bit of an issue where we were working on a problem in the lab, but that is three weeks ahead and we hadn't talked about it yet... the frustrating part about that is when you haven't learned the concepts and you're being graded on those mistakes." Students confirmed our existing views that the laboratory activities and students' experience with those activities was inadequate to foster the cognition and dispositions we were interested in developing.

Analysis of the statistical data between pre- and post- student populations (Table 1) using independent samples t-test/s shows that the changes initiated by the Physics Department had a significant positive effect on students' perceptions of their experiences and the nature of their laboratory learning environment. The large effect sizes confirm marked changes in students' perceptions. While these findings might seem predicatble, there are very few if any studies that provide anything other than anecdotal evdienvce on the effect of such changes, especially with such large student cohorts. In interviews, the students described the type of thinking they considered was required of them in the 2012/2013 laboratories and tutorials. They reported that they were given a starting point, a problem to solve, and from there they had to determine how to proceed, how to make sense of the problem, how to bring their learning from lectures, e.g., equations, to bear on the problem, and how the TAs, in general, provided guidance through scaffolding support without ever 'telling them the answer,' so that the students had to arrive at the end point themselves. Students in 2012/2013 were much more satisfied with their experience than those the previous year, even though the thinking they were asked to undertake might be considered more challenging, and certainly more inquiry orientated, than previously asked for. Examples of the 2012/2013 students' intimations during the interviews, woven together from their interview transcripts are immediately below. These clearly help identify differences between the perceptions of the 2011/2012 and 2102/2013 cohorts regarding their physics laboratory learning environments.

My labs take the whole three hours and all of the lab report is done after. They don't give you any guidelines. It's like, "This is the answer we want, here's maybe a hint, and then you have to go and figure it out by yourself. In the solar rotation lab, they basically told us what they wanted, with no hint of all of the math behind it and what we needed to use and what different equations to use. We had nothing to start with, just what they wanted [asked for]. And so, most of the stuff that we used was our own thinking... and then the laboratory instructor ended up helping us a lot because we were all clueless as to where to start to approach it. So, it was *all very much starting from scratch. [There was] a lot of talking and trying to figure it out. We take what we have done and what we can measure... there were about five of us trying to work it out together."*

I found that the way the labs were set up in Physics 124, it made me so relaxed that when I came into the labs I was encouraged to to learn about what the topic of the day was. Our laboratory instructor was really good, [saying] "This is a calm environment; you don't have to rush through the three hours." So, you can actually ask questions and learn more about it and learn things that you want to learn out of it, not just the basis of what the lab's about. The procedure for the labs is pretty much left to you. A good thing with the physics labs was that you could read ahead with the notes that your prof posted or you could refresh from the notes that you had already gone through, and then apply that to the lab that you're doing. You had that knowledge and it wasn't just coming out of random places that you had never experienced before.

I think they were looking for us to do a lot of critical thinking, not just how to plug numbers into formulae and spit out more numbers, but [to look at] the concepts behind it and how certain discoveries were made and how we could use these in our daily lives. In physics [labs] there's no ingredient list, there's no formula to follow. You have to figure out what you're doing.

Most of the thinking was, "How do you take a problem and work through it?" Most of it was word problems. They didn't just give you a formula and say "Go with it." YOU had to decide which formula you had to use, because sometimes they gave you a lot of formulas and you had to use one of them. Or sometimes they only gave you one formula and you had to derive the others. So YOU had to figure out which formulas to use and how to do it. I remember one lab, in particular. The quantum tunneling lab. There were a lot of theoretical questions about that, and you really had to think totally 'outside the box' as to how it happens or could possibly happen. In our group it sparked some pretty good discussions.

Concluding comments and implications

This study suggests that substantial change/s can be effected in undergraduate physics laboratory classes in settings where there are large numbers of students taking first year courses and multiple laboratory sections. This is an important finding for undergraduate science education nationally and internationally. It is also clear that new collaborations, in this case those linking Physics and Education faculty can result in positive outcomes for students, faculty and the university and that such collaborations should be promoted within universities. Further activities and studies are planned to build on these results from across other first year physics courses, to refine the activities already developed, and to develop and evaluate training programs for graduate teaching assistants.

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