Constructive alignment for deep learning: very short, argument-based laboratory reports

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Abstract

This case study describes a short-report assessment and feedback cycle in a physics laboratory course for pre-medical students. Students began with standard laboratory manuals but branched off at will to investigate concepts, methods and properties that they did not understand. They were encouraged to compare results with others and to incorporate group data to better overcome noise and bias, as well as to develop an appreciation for the roles played by instrumentation and good technique. Each experiment was assessed through a short report in which students presented an empirical case for conclusions of their own choosing with the length strictly limited to one page. The guiding criterion for marking was that the report had to be persuasive and significant. The space limitation forced students to decide which argument to present, at what level of detail, with what supporting data, and in what formats. Students were thus engaged in higher cognitive processes not often invoked in introductory teaching. Feedback explicitly addressed the writing and focussed on formulating and clearly expressing a thesis. Though the traditional physics content was unchanged, the open-ended, overtly empiricist format led many students to comment on how interesting, medically relevant and enjoyable the physics was.

Introduction

The purpose of pre-medical physics

Pre-medical physics courses in the United States are best understood within their historical context: they were designed largely in response to the Flexner Report from over a century ago (Flexner, 1910). Flexner urged at least two years of basic science before entering medical school, putting medical education firmly on a scientific foundation (Beck, 2004; Barr, 2011). Introductory science enrolments hence swelled, prompting the development of science courses targetted specifically towards meeting medical admissions requirements.

A century after Flexner, the purpose of pre-medical science, including the physics laboratory course, is again in question. Johns Hopkins Medical School (2015), for example, takes an epistemic approach, explaining that laboratory work should provide “practical understanding of the process of scientific inquiry and to gain insight into how scientific knowledge is discovered and validated.” In contrast, the University of Michigan (2015) seeks contextual application: “Clear evidence of the ability to demonstrate knowledge of basic physical principles and their applications to the study and understanding of living systems such as thermodynamics and fluid dynamics is required....” In 2009, the Association of American Medical Colleges (AAMC) and the Howard Hughes Medical Institute (HHMI) jointly issued a report, *Scientific foundations for future physicians* (2009), aimed at effecting the first major refreshment of pre-medical curriculum since Flexner. They recommended treating physics and chemistry under a single competency category, proposing sample assessment tasks such as “Describe the function of radioactive tracers for diagnosis of disease” and “Describe the role of signal processing in sensory systems and its significance for disease” (pp. 11–12). Aiming to open pre-medical education to greater innovation, the authors intend that such competence-oriented outcomes “should release the student from specific course requirements” (p. 2) and draw on high-level cognitive actions to generalise and apply knowledge across contexts, even if their assessment specimens operate at primarily declarative, non-investigative levels. The upshot is that medical students should do more than merely pass a couple of introductory physics courses: they should also make the physics useful, and be assessed for their ability to do that regardless of which courses they have taken.

In contrast to the ideals expressed above, student attitudes are shaped by pre-medical advisors who are more concerned about admission into medical school. The first twenty-five pre-medical advising websites found by a Google search on “pre-medical site:edu”, excluding those provided by medical schools, all provided students with the same guidance: take the required courses, spread the risk of doing poorly (e.g. “taking too many science courses concurrently can result in a stressful and academically disappointing term” (University of Pennsylvania, 2015)), and choose remaining courses to develop personal interests, perhaps also to support an alternative career. Such advice is also provided on the website of the American Association of Medical Colleges (2015). Indeed, while some advising sites mention that some medical schools are embracing the AAMC-HHMI competencies framework, many state explicitly that most medical schools still require a specific number of semesters of biology, chemistry and physics, including laboratory-based content. Accordingly, students are guided towards thinking about “requirements” and “pre-requisites” and are given checklists of institution-specific science courses that satisfy medical school demands.

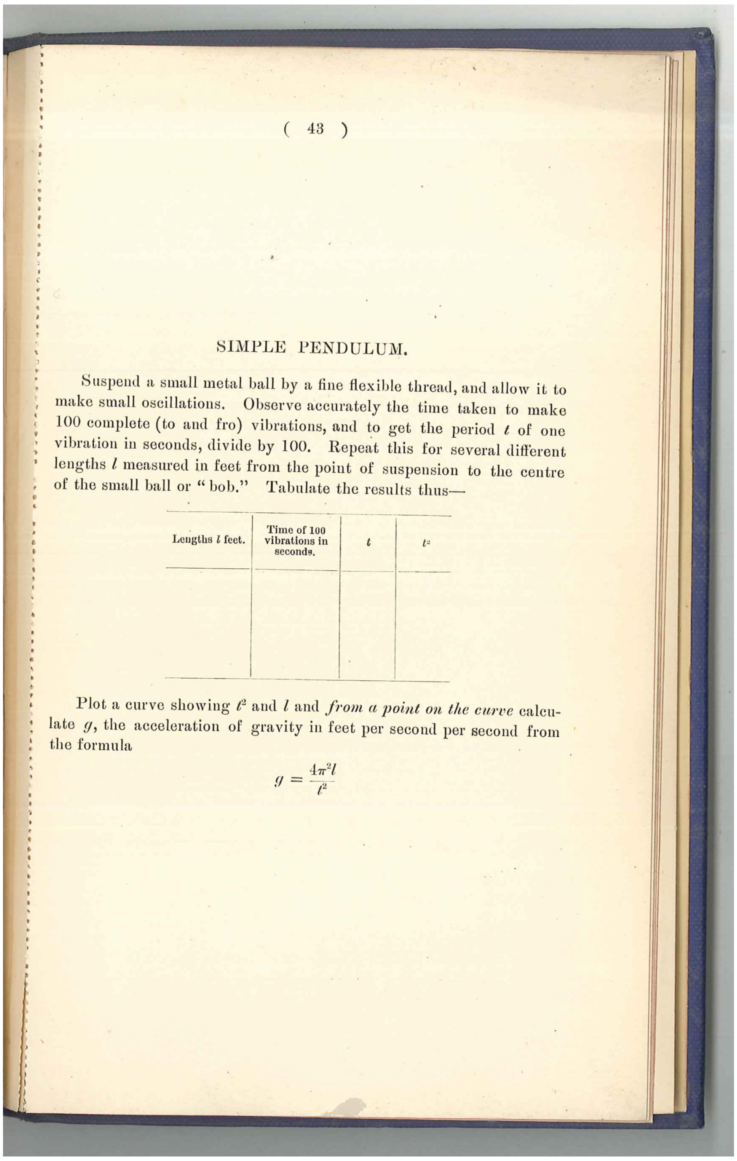
Pre-medical students commonly echo the pre-medical advisor perspective, speaking of physics as “a requirement” (often “irrelevant” and “useless”). At conferences across the United States, physicists commiserate about the challenge of sharing the benefits of physics with an audience so capable, yet so reluctant. That reluctance has been measured using the Maryland Physics Expectations Survey (MPEX), as has the tendency of traditional physics courses to make students more reluctant still (Redish, Saul, & Steinberg, 1998; Kortemeyer, 2007). Pre-medical students have been found to hold similar views of physics outside North America (Ribeiro, Severo, Pereira, & Ferreira, 2015), and negative sentiments have been observed across physics students more generally (S. Sharma, Ahluwalia, & Sharma, 2013). There does not seem to be a research consensus on why traditional physics undermines student enthusiasm but many instructors assume this is due to perceived irrelevance. Accordingly, instructors have re-designed their pre-medical physics courses around biological or bio-medical contextualisation (Sabella & Lang, 2014; Plomer, Jessen, Rangelov, & Meyer, 2010; Christensen et al., 2013; Crouch & Heller, 2014), sometimes with the *Scientific foundations for future physicians* principles and the Medical College Admissions Test firmly in mind (Thompson, Chmielewski, Gaines, Hrycyna, & LaCourse, 2013; Hilborn, 2013). Biological contextualisation dominates efforts to help pre-medical students but lacks an evidence-based rationale: pedagogical re-framing towards epistemic progress or model-building (such as inquiry-based learning) has been shown to generate positive attitudinal gains and increased engagement, but comparable outcomes for biological re-contextualisation remain to be demonstrated (Madsen, McKagan, & Sayre, 2015).

The intellectual purpose of pre-medical science learning is hence at odds with the practicality of getting accepted by a medical school. Both medical schools and the *Scientific foundations* report call for an approach to science that makes it useful. The desired learning outcome is not topic coverage but development of the ability to apply physics to understanding bio-medical processes and solving bio-medical problems. However, students see it as a hurdle and this is reflected in poor engagement.

Structure and assessment of pre-medical physics laboratories

From an assessment perspective, pre-medical physics tends to focus on declarative and algorithmic knowledge. Student laboratory manuals heavily emphasise the lower levels of Bloom's taxonomy for the cognitive domain (Anderson et al., 2001). They typically begin with lengthy theoretical pre-reading and contain very detailed instructions. Both theory and detail are gradually added over many years to compensate for content and technique that students no longer learn at secondary school. The manual for each single experiment is typically around ten pages long, in contrast to early twentieth-century manuals requiring only a page or less (see Figure 1 for an example from 1912). The emphasis on theory, and on closely following detailed cookbook-style instructions, had largely overshadowed the conceptual, methodological and epistemic learning goals exhorted by medical schools and by physicists.

Inquiry-based learning (Hodson, 1993; Russell & Weaver, 2011; Lindsey, Hsu, Sadaghiani, Taylor, & Cummings, 2012) offers a proven model to achieve the desired learning outcomes, but implementing this throughout a laboratory program is unfeasible without extensive time and support. Instead, guided by the principles of constructive alignment (Biggs, 1996), in this project I re-designed the assessment of a set of pre-medical physics laboratories to shift student attention towards open-ended, process-oriented learning, and to legitimise inquiry. The apparatus and manuals needed no great change. Under this arrangement, the assessment communicated and aligned with the learning objectives, and helped students to achieve them. The positive effects of this change in assessment on student engagement and learning outcomes are reported here.



(43)

SIMPLE PENDULUM.

Suspend a small metal ball by a fine flexible thread, and allow it to make small oscillations. Observe accurately the time taken to make 100 complete (to and fro) vibrations, and to get the period t of one vibration in seconds, divide by 100. Repeat this for several different lengths l measured in feet from the point of suspension to the centre of the small ball or "bob." Tabulate the results thus—

Lengths l feet.	Time of 100 vibrations in seconds.	t	t^2

Plot a curve showing t^2 and l and *from a point on the curve* calculate g, the acceleration of gravity in feet per second per second from the formula

$$g = \frac{4\pi^2 l}{t^2}$$

Figure 1. Excerpt from a historical undergraduate physics laboratory manual (Morley & Inchley, 1912).

Context

This case study took place in a small, highly-ranked United States research university offering undergraduates a four-year liberal arts degree course. Physics and chemistry are small majors, fluctuating between 10 and 30 graduates per annum out of approximately 1,300, whereas biology produces between 70 and 100 graduates per year. Thus, the approximately 300 students in the pre-medical physics courses are mostly not majoring in physics, chemistry or biology. Pre-medical students can enrol in physics during any year of their degree, and many postpone it until later years to reduce the perceived risks of taking too many high-stakes 'requirements' at once, and often in the hope of the course rotating to a preferred instructor or more generous markers. Pre-medical physics classes hence include students from all four undergraduate year-levels.

At the time of this study, pre-medical students were required to complete two physics laboratory courses. The first of these covered mechanics and heat; the second, optics, electronics, electromagnetism and radiation. Students attended weekly during regular term, or three days per week in summer term, to undertake an experiment approximately synchronised with the parallel lecture course. Within the laboratory, students worked in pairs or groups of three, supervised by PhD student demonstrators. Instructors monitored and helped with troubleshooting, coached demonstrators, worked with students and piloted various improvements. The course underwent changes in tone every few years when instructors rotated, and there were sometimes localised changes in administration or content that could persist or revert as the next instructor decided.

The assessment involved a laboratory report for each of the twelve experiments, cumulatively worth 70% of the final mark, with some iterations of the course excluding the two lowest-scoring reports to give students some flexibility. The reports were structured around the standard headings: aim, methods, results, discussion and conclusion, and were typically five to ten pages long. They were largely written outside the laboratory and submitted for marking during the subsequent laboratory class. The laboratory demonstrators marked reports and returned them one laboratory class later, so two classes elapsed between completing the experiment and receiving feedback.

The course culminated in a practical examination worth 30% of the final mark. This involved performing and writing up three one-hour experiments drawing on both theory and methods covered throughout the term. The experiments in the examination often combined ideas from two of the experiments already conducted, and many problems had multiple possible solutions but required only basic physics to keep the focus on broader methods and concepts. For example, a problem to determine the mass, density and volume of a brass block, roughly sawn from a hexagonal rod, drew on both statics and buoyancy, and the volume could be found less precisely, but still usefully, by direct measurement and simple calculation.

The course change described here was conducted during two consecutive summers, which each fitted the content of the regular twelve-week term into four summer weeks. Summer courses were chosen to pilot the assessment change because they were much smaller than regular term classes, with no more than sixty students, restricting the learning impacts and recovery logistics caused by any difficulties that might arise.

Results and Discussion

Structure of the modified assessment

The report design was inspired by the ‘extended abstract’ format used at the University of Melbourne. Students were assessed on a report strictly limited to one page, written outside laboratory hours. This required careful note-taking during laboratory sessions to inform a convincing and intellectually motivated empirical case for any claim supported by the students’ laboratory work. Notebooks were not assessed, but demonstrators provided students with in-lab guidance on how to think through their recording processes by anticipating what they might need to draw on later, and also how to use in-process tabulation and graphing to strategise continuing data collection so their data would capture patterns or signals of potential significance. The report’s short length necessitates conciseness, which in turn necessitates clear conceptualisation. Typical laboratory sessions produced multiple data sets, allowing a choice between report topics. Students thus had to evaluate which measurements supported the more convincing report, and also had good reason to engage critically in measurement processes in order to produce good data. Motivations could draw on practical applications, but equally acceptable were more intellectual concerns such as understanding a physical property such as springiness or conductivity.

The report format was open: students had to choose their own combination of prose, diagrams, graphs, tables to make the strongest possible point. They thus had to understand what kind of information or analysis each of those formats is best used for, in combination with evaluating what arguments they wanted to make. Because persuasiveness was paramount, the conventions and quality of graph-plotting were obviously useful rather than a mere compliance demand. Persuasiveness also made legibility into a student concern, heading off loopholes such as the use of tiny print to circumvent the page limit. Overall, the short report format was devised to focus attention on high-level cognitive activities, and liberation from the methodical approach that sometimes results from the traditional format (Aydeniz & Yeter-Aydeniz, 2015).

Open-ended inquiry: "ignore the instructions"

Changing the practical sessions to inquiry oriented learning would have offered a suitable model for reform, but such a large scale change was not feasible at the time. The main obstacle to such a change was the laboratory manual. Instead, it was hoped that the change to assessment would communicate the importance of undertaking inquiry. It is only natural for students to feel obliged to follow the laboratory manual instructions, stressing completion and compliance ahead of learning. One obvious reason is the customary authority of official texts. Another is the importance of compliance for safety, accountability and logistics. In the courses concerned, the range of apparatus in use made such needs minimal, so there were few risks associated with telling students to depart from the instructions under demonstrator supervision. Students were told to keep their report-writing goals in mind, start with the laboratory manual, and to break away and investigate their own questions as soon as they had a problem of their own. Students were also told that it was permissible to compare their data with that of others, and to aggregate data from the whole class, whether to check their own measurements or to achieve better measurements overall.

This policy was motivated by three considerations:
1) to allow students to focus on learning, rather than completion;
2) to increase intrinsic motivation associated with sating personal curiosity through personal autonomy and through consciously building one's own competence;
3) to provide natural opportunities for engagement with problem-driven experimental design and with data collection processes (such as strategising measurement density to optimise pattern and signal detection), and for honing techniques in response to measurements.

There was good reason to think such a move may be risky: without clear content delineation, how can students be sure of learning correct content (Olsen, Hewitt, & Lyons, 1996) or know what to learn for the examination (M. D. Sharma, Mendez, Sefton, & Khachan, 2014)? These concerns were answered by the assessment design: the report task was naturally satisfied by problem-driven inquiry, and the examination tested experimental skills associated with problem-driven inquiry and quality-oriented practice.

Impact on student engagement, behaviour and learning outcomes

Students' desire for better data was motivated superficially by the demand for a convincing empirical report, which illustrates the importance of designing assessment to communicate desired outcomes. As the course proceeded, students became more attentive to adjustment, calibration and measurement technique. Students gradually came to value good data as an intrinsically valuable outcome, speaking in class about accuracy, precision and reliability in physics as analogous to the same goals in medicine.

Students who pursued their own questions typically investigated special cases through which they solidified their understanding of the standard exercises. Such actions suggest that we underestimate how much experience and demonstration students need to form a sound understanding. Sometimes they attempted to generate a counterexample and discovered empirically that it did not work. This was especially noticeable during electronics labs, when students frequently devised shortcuts on the basis of incorrect circuit theory. In many cases, they repeated qualitative experiments over and over, watching, for example, light bulbs switching on and off in parallel.

In some cases students suspected that a problem with their technique or the experimental design generated the result, rather than a general principle, so they wanted to see the same result demonstrated in a different way. The diffraction masks in particular elicited many re-orientations to test whether it mattered that the opaque emulsions were on the front or the back of the transparent glass and plastic substrates. Lenses, too, were often rotated and the images checked for consistency, even though the lenses looked symmetric.

Students found some experiments as written too simple and sought more complex examples to extend and generalise the standard case studies. Adjacent laboratory groups pooled apparatus to convert their simple two-lens telescopes on the optics bench into complexes of many lenses, for example, and improvised three-dimensional objects in place of the two-dimensional ones treated in textbooks. This made it possible for students to touch on higher-level imaging concepts such as depth-of-field, entrance and exit pupils and vignetting, applicable in the design and use of optical instruments (hence often depicted in biology course materials concerning microscopy) but commonly omitted from introductory physics textbooks.

Characterising and managing the complexities of freeform practice required some adaptation by students. For example, thermistors provided to track the temperature of a cup of warm water gave readings different from each other, and students initially concluded that at least some of their probes must be damaged. They were directed to borrow a spare probe from another pair, and soon discovered that nearly everyone faced the same situation. Many lost faith in electronic measurement at that point, and requested alcohol thermometers instead. When the alcohol thermometers were brought out, students saw that the alcohol thermometers' readings also varied slightly. As a result, a few students took it upon themselves to tabulate all of the alcohol thermometers' room temperature readings in a spreadsheet and calculated the mean as their best available calibration standard for the whole class to use. Thus, from perceiving defective manufacturing, the students progressed to engaging with the inherent imperfection of instruments and the compromises needed to work with them. Calibration and regression emerged naturally in this case; it did not need to be taught. We had not planned this problem; it had not eventuated in the past because students received only one sensor, so never noticed that readings differ.

Complexity was also addressed when fuses blew. For example, the DC electrical supply was provided through sockets in the laboratory benches via DC cables containing an in-line fuse. The fuses had long frustrated laboratory instructors, who commonly carried replacements in their pockets because fuses blew so often. Under the new régime, the blown fuse became the students' problem. It turned out that none knew what a fuse is, so they were directed to unscrew the fuse holder to see for themselves. They were given a new fuse to compare with the old one. Visual inspection revealed the tiny wire inside the glass cylinder, melted through with curled, broken ends when a fuse had blown. Continuity testing with a multimeter showed that only the intact fuse conducted. Many students were amazed by this revelation, and asked to keep their first-ever blown fuses as souvenirs. With the mechanism understood, the incidence of fuse-blowing declined sharply, and students were able to diagnose and replace fuses that did blow. Students had conceptualised that 'to blow a fuse' meant 'to fuse' (i.e. melt) it, hence its name. Sacrificing the fuse prevented their work from being damaged similarly. That knowledge empowered them to adjust their work processes to protect not only the fuse, but their whole circuits, from excessive currents. Students thus engaged in the interplay between theoretical knowledge, experimental design and experimental technique.

Systematicity manifested in the students keeping their benches tidy, and cleaning up afterwards, upon learning that a messy bench undermines the ability to distinguish signal from noise and makes it hard to interpret measurements. The previous laboratory culture had students leave apparatus for technical staff to tidy up. The change was so marked that a departmental administrator asked why the class had been cancelled, having misinterpreted the tidiness as a sign that the students had not been in at all.

In all of these cases, the students were practising aspects of scientific inquiry, and perhaps also addressing their unfamiliarity with the logic of empiricism and science's heavy dependence on induction. The students' willingness to spend considerable time on such activities may indicate a need for much more experiential exploration, even structured play, rather than the minimalist demonstrations of physical laws in which experts find beauty and elegance (van Gigch, 2002; Stevens, 2003), and on which many laboratory exercises are based.

Many students also addressed misconceptions. One pair of students, for example, asked for more patch cables because they had plenty of black cables but not enough red ones to build the circuit shown in the manual. They expressed concern that using cables of the wrong colour would make the current travel in the wrong direction. I supported the demonstrator's explanation that the cables all had the same metal inside (as could be seen by unscrewing the terminal casings), but held that the ultimate test was really in experiment, not in arguing from theory or appeals to authority. The students, still committed to their belief, then spent the entire laboratory session trying to build a counterexample, at times confused by the need to control current direction through the ammeter and voltmeter. The counterexample proved more elusive than anticipated so they had to systematise their search, and think through what the meters actually do, in addition to their many circuit designs. In this example, the students were driven by intrinsic motivation to understand a basic phenomenon. They discovered that complex experimental design needs to be systematised, and that theory, experiment and instrumentation all interact: the three are interrelated, entailing careful consideration about whether an experimental design tacitly assumes that the hypothesis is either true or false. Such complexities released us from having to 'teach' them about meters; their problem provided good reason for them to look this up on their own.

One downside was that the attention to data quality and fulfilling curiosity often led students to be so engrossed that they lost track of time and had to be interrupted. While it was wonderful to see such deep engagement, there was clear scope to assist students with planning and to guide them towards data adequate to answer the question at hand.

Feedback to students on notebooks and short reports

Laboratory demonstrators are not always skilled teachers, and postgraduate students are often assigned this role as an opportunity to begin developing their teaching skills (Volkmann & Zgagacz, 2004; Seung, Bryan, & Haugan, 2012; Lin, Henderson, Mamudi, Singh, & Yerushalmi, 2013). The laboratory demonstrators in this case had acquired, from their own undergraduate experiences, strong ideas about how teaching laboratories operate, but they had not all had time or sufficient opportunities to conceptualise marking and feedback as acts of teaching, rather than as measurement and correction. Their marking was therefore scaffolded with a pre-made rubric (Figure 2). The rubric had only a small number of categories to focus attention, weighted to indicate emphasis, and a small space to keep further comment short. Demonstrators assigned only whole-number scores. To keep emphasis on the big issues and to avoid overwhelming students with too much small-scale feedback, demonstrators were asked not to write in the students' notebooks or on their reports. Demonstrators received reports at the next lab and marked outside laboratory hours, causing a delay in feedback.

Student: ____________________ Experiment: ____

NOTEBOOK RECORDS	
Legible	___ /5
Experiment, date, workstation, collaborators etc. recorded	___ /5
Apparatus, procedures described	___ /5
Measurements & observations recorded	___ /5
Total	___ /20

REPORT	
Experiment described (includes diagrams if used)	___ /5
Observations, measurements summarized (includes graphs if used)	___ /5
Insights & synthesis	___ /5
Expression (includes clarity, spelling, grammar, legibility)	___ /15
Total	___ /30

Figure 2. Marking rubric for assessing notebooks and one page laboratory reports.

Strategic, actionable feedback could not be reasonably expected of the demonstrators, so I provided it as the instructor. To avoid increasing the feedback delay, demonstrators gave marked reports to me at the beginning of each laboratory session so that I could work through them immediately. I aimed to give feedback on at most two items per report, chosen as foundations needed to support higher-level achievement in subsequent laboratory sessions. My instructor-level feedback was grounded in a humanities perspective, in which writing is construed as a process for thinking and learning. This writing-to-learn (WTL) pedagogy (Zinsser, 1988) has been useful in many disciplines, including for conceptual gains in physics (Hein, 1999; Rivard, 2006; Hand, Gunel, & Ulu, 2009), and can be incorporated into inquiry learning (Walker & Sampson, 2013). To succeed, WTL requires close attention to the writing itself, and feedback strategised to match what the writer needs at that particular moment (Fry & Villagomez, 2012). Prompts may progress from the simple declarative levels at the bottom of Bloom's taxonomy, rising to the higher critical levels as student writing shows readiness for them. WTL feedback is directed towards the writing, not towards the content, so that the writing process drives thorough, critical thinking about the physics. Following a strategy common in the humanities, I chose a three-part formula aimed at providing a conscious understanding of the problem plus guidance on how to do better: (1) state what is wrong, (2) explain why, and (3) describe how to fix it (Brookhart, 2008, chapters 2 and 3). Providing feedback on the previous week's report for sixty students took approximately 90 minutes of each three-hour laboratory session, less than two minutes per student. I then returned the reports directly to the students, and joined the demonstrators in the laboratory.

Practical examination

There was no need to modify the examination format described above because it already tested the empiricist skills sought. The change made was to re-construe the practical exam so that it reinforced the motivations behind experimentalist processes such as taking multiple measurements, plotting graphs, and finding gradients of fitted lines. Such activities should be done to fulfil intended purposes, such as to characterise and constrain statistical error, to seek patterns, or to compute a physically meaningful rate or proportionality. With only one hour to conduct and write up each experiment during the examination, it was important for students to understand which processes would help in which ways - there would be little benefit in extracting a graph gradient, for example, when the axis intercepts relate to the physical information.

Student response to the modified assessment

Students responded positively to both the report format and the WTL feedback. Almost all student feedback was informal and many took advantage of the laboratory's open culture to comment during laboratory time. Students were initially suspicious of the autonomy expected. Some later reported that it was commonplace to be told to follow their own curiosity, but this was the first time an instructor had provided an assessment framework in which grades would not suffer for that.

The one-page reports were initially tentative, but improved rapidly. Actionable feedback about writing was received positively and was appreciated as a kind of learning support otherwise scarce. Many students commented that they were learning about writing and physics in spite of having expected to learn about neither. Many also spoke about how they were seeing the applicability of physics to medical apparatus and biological processes, that empirical process provides a basis for medical diagnosis, and the importance of asking how strongly a model is supported by its evidence. A few students noticed the connection between error analysis and Bayesian probability calculations, explicitly struck by the realisation that medical diagnostic results (which come with probabilities of false positives and false negatives) cannot be taken at face value.

Students found the hands-on examination challenging but feasible, and an affirmation of what they were there to learn. One wrote in the end-of-course feedback that the final exam did a very good job of testing whether students had learnt to think about physics and how to approach experimentation rather than merely duplicating content taught and assessed in the lecture course. Also among the scant written feedback received was grateful acknowledgement that the course was about significant learning, rather than just getting a grade and moving on.

Conclusions

The assessment that we set conveys strong claims about our values and about what students ought to work on and learn. While assessment remains important for post-factum accreditation, it can serve equally as a curricular device for shaping student learning. Aligning assessment with desired learning objectives can achieve wide-ranging impact with far lower investment than would be required for comprehensive course redesign. Adopting an open-ended, narrative-based, one-page report format in this study within a service physics course achieved multiple outcomes:

1) students focussed on experimental physics as a scientific inquiry process;
2) students engaged with physical concepts in order to be able to write clearly about them;
3) students engaged with data quality and meaningful error analysis;
4) students developed intrinsic motivation to take physics seriously;
5) staff bore no greater administrative load.

Feedback to students each week nudged them towards the particular kinds of inquiry required, and drove their engagement with concepts and data into alignment with appropriate physics learning objectives. The feedback system used depends on having someone available to provide report writing feedback that can drive appropriate thinking about physics. The skills of teaching writing are usually associated with the humanities, so physics laboratory demonstrators may not be able to perform in this role. The burden may thus fall on the instructor, who may have to learn how to teach writing.

Through the writing-centred feedback, students learned that making convincing arguments in their reports requires them to choose methods appropriate to the problem under study. Because the topics were all physics, standard physics methods worked well. Thus, students actively considered what those methods achieve as part of formulating a strong rhetorical strategy, and thereby learned about the nature of physics in an epistemic way transferable to medical and other studies.

Emphasising process and the nature of science may seem to risk loss of content. This case study demonstrates the feasibility of leaving content somewhat under the students' control in a service unit in which the processes and intellectual spirit of the science are paramount. Students were not completely unsupported since they started from the laboratory manual and took a lecture course in combination with the laboratory course, and had laboratory demonstrators, the instructor and each other at hand during laboratory sessions, in addition to unrestricted access to textbooks and the world wide web.

Most importantly, the students spent most of this course loving and learning a subject that they had expected to be irrelevant, useless and unpleasant. It is clearly possible to teach physics for its own sake, emphasising the epistemic character of physics as a source of insight both inherently worthwhile and transferable to other fields of study, even to pre-medical students.

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