Undergraduate practicals must involve real science.

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Standing in the bustle of a busy teaching lab, you are enveloped in the sounds and smells of chemistry – rotavaps spin, stirrers whir, and Büchner filters hiss. On the face of it, practical work is a good thing. Ask any academic what practicals are for and you will get a range of answers, from experiential learning, to training in techniques, and the reinforcing of theoretical ideas learned from books or lectures. University websites extol the virtues of laboratory classes, speak of the learning that takes place in labs, and of the useful time management skills that accrue to students during these periods.

And yet, anyone who has "demonstrated" in a lab will remember the student who, holding a flask containing a pale yellow solution, asks "Is this blue?". This is the stuff of pub conversations accompanied by a sigh. "Students these days…". But such smugness is misplaced. This is a student whose confidence in the lab has been eroded to the point of being unable to make what appears to be a simple judgement. That this should happen, however rarely, is an indictment of the failure of some of our practical classes to achieve their objectives. While some students thrive in the lab, for many the end of practical classes is time for celebration.

For many academics, practicals are supposed to provide students with an introduction and an insight into research. For Paul Nurse, Director of the Crick Institute, "Finding things out for yourself is at the very heart of science."[1] and has vigorously contested changes to curricula that appear to reduce the extent of practical activities.

Yet, study after study has shown that in contrast to the best intentions of teachers, laboratory sessions, far from being exciting opportunities for learning, are instead a time of drudgery and sources of anxiety for students who feel acute pressure, the result of cognitive loads identified by Abrahams and Millar a decade ago.[2]

So are the "experiments" that our students do in our teaching laboratories "finding things out for themselves"? Here it is very important to define terms. An *experiment* is what a scientist does to interrogate nature. We conduct an experiment when we don't know the answer. So we might react A with B expecting to get C. In other words, if it really is an experiment, then the outcome is uncertain. This is very different from what students do in our labs. Although we typically *call* them experiments, they are procedures that have been rigorously vetted to ensure that a particular outcome is obtained reliably. Anything else would cause chaos, especially from the perspective of assessment. So if a student measures the enthalpy of vapourization of cyclohexane, the value they determine can be compared with the literature – this comparison then typically forms part of a marking scheme.

So in reality students are not doing *experiments* but rather assessed practical exercises, an distinction that has serious consequences. When students do practicals they do so from a position of intellectual safety. They are cradled by the certainty that there is a right answer and that anything else will be assessed as having a particular degree of wrongness. At the same time, the teacher is entirely safe. They know what the answer *should be* and can rule, safely, on the student's ability.

But without wanting to downplay the importance of training students in techniques, do our practicals expose our students to the actual process of science itself? In stark contrast to the intellectual safety of a typical undergraduate practical, in a research experiment you are much less certain of what the answer should be. This is a totally different world in which you cannot so easily turn to your neighbour in the lab and ask "What value did you get?" but are forced to think critically about every step of the intellectual chain of custody that links your glassware to the conclusion your write in your report. In addition, in a lab where 100 students conduct the same procedure, should we be surprised if we observe a certain degree of "collaborative convergence" on a particular result? This certainly happens if a mark depends on it. And to make matters even worse, the need to assign students individual marks leads us, perversely, to actively dissuade students from working together, in spite of collaboration sitting at the core of modern scientific activity.

The educational literature is full of studies that show that providing pre-lab material, on paper and on video, along with online testing is a useful way of helping students to cope better with the labs, and that this leads to improved, though often narrow, learning outcomes. These are unquestionably popular and effective innovations. Inspired by P J Alaimo's example,[3] we have also modified lab sessions to give students multiple variants of a particular procedure such that the class generates a dataset that can be discussed in recap seminars – each student's data provides a small piece in a wider theoretical jigsaw. Importantly, by personalizing each student's task, this approach aligns collaboration with learning.

Yet a key weakness of our current approach to practical teaching is that students are always replicating something known rather discovering something new for themselves. Until they embark on a research project in their final year, they seldom participate in the process by which scientists come to be confident in the correctness of something previously unknown, and the chain of reasoning that leads to this. That science is able to do this is almost miraculous, and the doubt and uncertainty inherent in the process is at once the scientific method's extraordinary strength, but also, in the current political climate, its great Achilles heel. Exposing both children and undergraduates to this process is thus societally critical if we are to combat the increasingly prevalent suspicion of science.

In order to join these many dots we decided to develop a new activity for our students that would at once involved the measurement of something unknown both to students and to staff – levelling the playing field – and also shift the focus from "the answer" to the actual process by which the final results would be obtained. The idea for the project arose when my Engineering colleague Muki Haklay introduced me to the Palmes diffusion tube method for measuring NO_2 in the local environment: air diffuses into a tube of known dimensions, the NO_2 is captured chemically as nitrite, and can then be quantified colorimetrically using a diazonium reaction. In other words, we envisaged a traditional Beer-Lambert law practical, but one conducted on a system our students were likely to care about: the very air that they breathe. The method can be reproduced easily and, provided one has well-maintained UV/Vis spectrometers, can be done at very modest cost.

The idea was for our students to conduct a large scale study of air pollution across London. This would be real research in the scientific sense of finding out something new, rather than the colloquial "looking things up". Given the societal importance of the issue of air pollution, we decided that our students would work with classes of London schoolchildren to design the study. The children, local experts, would choose the locations they were interested in; our students, many of whom are new to London, would report back to them on the results.

Crucially for me, this would help our students see science in the round – from theory, to experimental design, to analysis, and reporting; a long project that would give them the opportunity to think for several weeks about an issue. By connecting with a local community, they would have sense of real responsibility for the quality of the lab work they would undertake. From a wider perspective, they would see the inside of a primary school. For the children, our students might be role models; conversely a few of our students might one day be inspired to be primary school teachers. Teaching, research, outreach, and teamwork fully integrated into a coherent activity.

The complexity of the project was not for the faint-hearted. 140 students visited 35 classes across 19 schools, talking to well over 1000 children and collecting 400 diffusion tube samples. If the data they obtained were variable in quality, that was almost a bonus: we had doubt and uncertainty in spades. But each set of tubes showed trends broadly consistent with the hypothesis that air pollution in London is mostly due to motor vehicles. One group, who forgot to uncap their tubes, got a set of null results. Would they score zero? Of course not, I replied. Theirs was a control experiment.

It is quite clear that many of our students were pushed well outside of their comfort zone – the idea of doing a practical without being able to look up an answer was shockingly new; there was the added excitement given the topic's prominence in the UK courts and political discourse. The data mattered. If placing and collecting the tubes was rather tedious, the in-class sessions were exceptionally rewarding, as was having a small team of peers to work with very early in their time at university. Most of the schools we visited have invited us back, citing how the project had started conversations not simply with children, but also with parents about pollution and how to tackle it. More importantly, at a time when expertise and knowledge are derided by some politicians and pressure groups, it has never been more important for us, as educators, to bring out into the open, as early as possible the mysterious process by which we arrive at our understanding of the world, and the doubt that accompanies it. We need to expose our students to the idea that the science we do has profound ethical and political implications. Science has traditionally been presented as a succession of truths and certainties, and more recently in the press as a constant stream of attention-grabbing claims. What we as educators and communicators of science sometimes elide from our practical teaching, is the very process by which we arrive at what we know. It is time that we started to redesign some of our practicals to think beyond the details of the glassware and the spectroscopy and instead to empower our students by helping them to experience first hand *how* we explore the world and how to communicate our endless fascination.

As one of our students put it “Before I touched this project my idea of science was to stay in a lab and do research on something that 99.99% of people… will never know. And it turned out that I was totally wrong. The point of science is to help people understand something new. If I can’t explain to people step by step in a simple way then it simply means that I don’t understand it either. That ruins science.”

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