Rethinking practical classes

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Undergraduate practical classes that include more real science are to the benefit of students, teachers and society more broadly.

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 an academic what practical classes are for and you will get various answers, including experiential learning, training in techniques and the reinforcement of theoretical ideas learnt 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 students accrue during these periods.

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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. Take a step back and here you see 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, even rarely, is an indictment of the failure of some of our practical classes to achieve their objectives. Although some students thrive in the lab, for many the end of practical classes is a moment to be celebrated.

For many academics, practicals are supposed to provide students with an introduction and insight into research. For Paul Nurse, Director of the Francis Crick Institute and former president of the Royal Society, "Finding things out for yourself is at the very heart of science" (*Guardian (Lond.)* http://go.nature.com/2y-IpcCj; 6 Feb 2016), and he 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 source of anxiety for students who feel acute pressure, the result of cognitive loads identified by Abrahams and Millar (*Int. J. Sci. Educ.* **30**, 1945–1969; 2008) a decade ago.

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 do not 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 most often do in our teaching labs. We may call our undergraduate practicals 'experiments', but in reality they are rigorously vetted procedures for which a particular outcome is reliably obtained. Anything else would cause chaos, especially from the perspective of assessment. So if a student measures the enthalpy of vaporization of cyclohexane, the value they determine can be compared with the literature; this comparison then typically forms part of a marking scheme.

> "do our practical courses expose our students to the actual process of science?"

I would like to argue, then, that when students do their work in our teaching labs, they are not doing real experiments but are rather conducting practical exercises — and this distinction is more than merely semantics. When students participate in practical courses 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 a student's ability.

Without wishing to downplay the importance of providing training for particular techniques, we must surely ask: do our practical courses expose our students to the actual process of science? In stark contrast to the intellectual safety provided by a typical undergraduate practical, in a research experiment you are much less certain of what the outcome will 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 that you write in your report. When 100 students all conduct the same procedure, should we be surprised if we observe a certain degree of 'collaborative convergence' on a particular result? This is certain to happen when a grade depends on closeness of the student's observation to a previously recorded result. And to make matters even worse, the need to assign students individual marks leads us, perversely, to actively dissuade students from working together, despite collaboration sitting at the core of modern scientific activity.

The educational literature is full of studies showing that the provision of pre-lab material — be it on paper or on video — in combination with testing helps students to cope better with practical classes; learning outcomes, though often narrow, are improved. These are unquestionably popular and effective innovations. Inspired by the example of Alaimo and co-workers (*J. Chem. Educ.* **91**, 2093–2098; 2014), my colleagues and I at University College London (UCL) have modified our laboratory practicals so that students each work on a variant of a particular procedure; they generate a larger dataset that can be discussed in recap seminars. In this way, each student's task is personalized while aligning collaboration and learning.

Yet a key weakness of our current approach to practical teaching is that students are always replicating something known rather discovering something new. Until they embark on a research project in their final year, they seldom have a chance to 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 extraordinary strength of the scientific method, but — especially in the current political climate — its Achilles heel. Exposing both children and undergraduates to this process is thus societally crucial 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 first-year students that would at once involve the measurement of something unknown to both students and staff. In doing so, we would level the playing field and shift the focus from 'the answer' to the process by which the final results would be obtained. The idea for the project arose when my colleague at UCL Engineering, Muki Haklay, introduced me to the Palmes' diffusion tube: a device for measuring NO_2 in the local environment. Air diffuses into a tube of known dimensions, and the NO_2 is captured chemically as nitrite, which 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 of doing a practical without being able to look up an answer was shockingly new"

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 simply '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 — the definition of 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, 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 a 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. 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."

The complexity of the project was not for the faint-hearted: 140 students visited 35 classes across 19 schools, talking to well over 1,000 children and collecting 400 diffusion tube samples. If the data they obtained were variable in quality, then that should be considered 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 our control experiment!

It is quite clear that the project pushed many of our students well beyond their comfort zones. The idea of doing a practical without being able to look up an answer was shockingly new; there was also added excitement given the prominence of the topic 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, with children and parents alike, about pollution and how to tackle it.

Perhaps most importantly, at a time when expertise and knowledge are derided by some politicians and pressure groups, it is essential that we, as educators, open up the mysterious process by which we arrive at our understanding of the world and the doubt that accompanies it. We must 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 practical activities by thinking beyond the details of the glassware and the spectroscopy, and instead empower our students by helping them to experience first-hand how we explore the world and how to communicate our endless fascination.

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