1. Title: REINVENTING ORGANIC CHEMISTRY TEACHING LABORATORIES

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2. Keywords
chemistry, laboratory, enquiry, experiential, research

3. Summary
We have reinvented the role of Warwick Chemistry undergraduate teaching at Level 1, with the aim of putting learning through practical experience at the front end of the undergraduate learning experience.

Specifically, we have:

- Reinvented the Organic Chemistry unit at Level 1 (*ca* 100 students) to make it enquiry-based in nature.

- Evaluated comparatively students' attitudes to laboratory teaching through "traditional" and "enquiry-based" laboratory classes.

- Exemplified the possibility of using laboratory classes as primary methods of exposing students to new aspects of theory.

- Started to disseminate the experience gained to the rest of the Department, Faculty, Institution and wider HE sector.

4. Activities

4.1. Background
That an enquiry based environment for laboratory teaching is educationally superior to those based on following detailed procedures is well documented; indeed, it is such a commonplace as to be included in a number of influential policy documents and suchlike [Barnett, 2001; Boyer Commission, 1998; Dobson, 2002]. As a result, many Departments of Chemistry now claim to offer experiential laboratory training. However, it appears that not all these claims are valid. For example, consider the following excerpt from the University of Calgary web pages:

<u>*Experiential learning*</u>*. Chemistry is by nature a practical, experimental science and so requires development of laboratory skills. In the laboratory component of all core chemistry courses, students make and record observations. They also learn the practice of fundamental experimental techniques and design, and the analysis and communication of experimental results (through experimental reports). Lab work helps students to acquire and utilize practical skills while relating theory to chemical reality.*

While it is clear that placing students in a laboratory environment, as described here, will result in them having an experience, it is less clear that such an experience will result in experiential learning. Furthermore, the experience may not be at all pleasant. For example, chemistry students at the University of Glasgow recently rated their laboratory classes as their least enjoyable activities [Paschke 2005].

This situation has been analysed by many and relatively recently in the results of a study funded by the Portuguese Science and Technology Foundation [Teixeira-Dias 2005].

In a typical [...] chemistry laboratory manual, little is left to the student initiative or circumstance: all the laboratory [...] procedures are carefully listed [...] in the provided manual, and frequently the student is simply asked to fill in [...] spaces [...] in a [...] well planned report template. At the end of a laboratory session, the student did not have a real opportunity of understanding or learning the process of "doing chemistry".

By contrast, if the student is to engage in deep learning in a laboratory session, it is important that he/she has the chance of identifying the main objectives of the work, of planning and executing it, of identifying the conceptual and practical difficulties encountered, recording and discussing the results and observations and [...] of suggesting practical alterations and improvements.

The authors then describe a laboratory class in which students are free to use the, necessarily rather basic, equipment available, tutors provide orientation rather than instructions and reports are in a reflective rather than structured style.

But an enquiry based approach to laboratory teaching does not only have advantages at the module level. Traditional lab classes tend to *follow* lectures or equivalents in which the underlying theory is delivered, the assumption being that it is not possible to carry out experimental work without the necessary grounding in theory. This line of thought seems particularly odd where the courses are being delivered in research institutions, since the very nature of research in science is to learn from experiment.

Of course there are examples where this tradition has been changed. The report of the Boyer Commission [Boyer Commission, 1998] refers to Rensselaer Polytechnic Institute which:
has redesigned its large introductory science courses for more effective presentation; the traditional format, in which lecture recitation, and laboratory sections were completely separate, were replaced by a 'studio' format, which integrates the three into one unified program taught in a single facility designed for the purpose.

In summary, there is ample evidence that enquiry led laboratory teaching has a significant positive impact on a student's ability to learn both the desired practical skills and also the underlying theory. It was not the purpose of this programme to "reinvent the wheel", but to apply these ideas in a simple manner to the Organic Chemistry laboratories at Warwick and capture in a narrative sense the impact on the students. We hoped that positive outcomes from the project, expressed in such narrative, would aid the bottom-up spread of enquiry based labs through the rest of the Department and Faculty and hopefully further.

5. OUTCOMES

All four objectives were achieved. The resources allocated by the Reinvention Centre were sufficiently generous to permit appointment of an outstanding Assistant for five months. Dr Jo Geden has a PhD in Chemistry and experience of teaching Chemistry in both secondary and tertiary sectors and was ideally suited to this programme.

5.1 Objective 1: To reinvent the Organic Chemistry unit at Level 1 (*ca* 100 students) to make it enquiry-based in nature.

Method. Introduction of new laboratory experiments carries significant resource implications for a Department, both in technician time in trialling them and in purchase of materials and equipment. We therefore proposed to minimise the need for this in order to maximise the chances of the educational context being adopted.

In fact, many of the "tried and tested" experiments used currently are perfect for reinvention. In general, they have been designed to illustrate an important point of theory and to give useful results in a relatively short time with a large group of students. An example of how this can readily be done follows.

Previously the students had been told that addition of bromine to a particular alkene would give a particular one of the two possible isomeric products, this illustrating an important stereochemical issue. They then carried out the reaction and proved that they had indeed made the expected isomer.

In the reinvented version of the experiment, the students were instead asked to think about the possible isomers that could result from addition of bromine to the alkene, to carry out the reaction (less experimental detail was given than previously) and to devise and carry out a simple test to identify which isomer was produced. This simple reinvention led to the students having to:

- think about the stereochemical possibilities in such reactions;
- elucidate the details of the experimental procedure;
- devise a diagnostic test.

We sought to reinvent as many as possible of the existing experiments along these lines. Additionally, we did not hesitate to include techniques for which the students were not yet prepared (safety permitting), believing that with some guidance they would better learn this material through experience.

Results and Discussion. Analysis of the six existing experiments in the Unit suggested that five of them could be reinvented as described above, though one was unpopular with students, as judged from previous years' feedback forms. The sixth relied on analysis being carried out for the students by technicians in "black box" mode, the students were able neither to devise the analytical protocol themselves, nor to carry it out themselves. The analysis also showed that experiments had been designed to fill the allotted time in the timetable with practical manipulations, leaving the students little time to work thoughtfully to solve the problem they had been set.

It was decided to remove both the unpopular and the unreinventable experiments from the Unit, to spread one very long experiment over two days and to remove sections from the remaining experiments to give more time for planning and reflection. Finally, a new experiment, readily adapted from the literature, was added in consultation with the technical staff.

Importantly, the impact of the changes on resources was, as planned, low. For the four (which became five) experiments retained no additional calls on equipment, consumables or technician time were required (indeed these were reduced in some cases). The addition of one new experiment to a Unit would be considered "normal" and was designed in consultation with technicians to have a low resource impact.

The impact on the laboratory manual was significant; most sections required extensive revision. In particular:

- each experiment was restyled as a problem to be solved, with all references to the expected outcome removed;
- more comprehensive references to textbooks were added;
- learning outcomes were revised;
- assessed questions relating to both theory and practice that were, as is "normal", set subsequent to the class were instead given at the start of each experiment;
- experimental procedures were changed to be, insofar as was sensible with safety considerations in mind, in the style of methods published in research journals;
- mark schemes were completely revised.

All the above was revised again in readiness for the 2007 class (in numerous very minor ways) in light of the feedback received.

The impact on the teaching staff was relatively light, though we did not anticipate the effect it would have on postgraduate teaching assistants (*vide infra*). The main changes were to the "prelab" sessions. Since students had carried out work *before* the scheduled lab session, it was necessary for these sessions to be more responsive. The traditional whole class prelabs were deemed inappropriate and more interactive, smaller group sessions were thus organised in parallel, many being led by postgraduate demonstrators. Apart from this, the main effect was to force teachers to support enquiry, rather than give straight answers, which is in any case good practice.

5.2 Objective 2: To evaluate comparatively students' attitudes to laboratory teaching through "traditional" and "enquiry-based" laboratory classes.

Methods. Evaluation of students' attitudes was attempted in three ways:

- at the very start of our programme, through a focus group of Year4 students engaged in advanced research projects who were asked to reflect on their entire training and consider the hypothesis that more enquiry-based lab classes were better preparation for research than traditional ones;
- through comparison of marks and feedback data from the Year 1 Organic Unit before and after the "reinvention";
- through a focus group of Year 1 students subsequent to the reinvented Organic Unit and during a "traditional" Inorganic Unit with very similar intended learning outcomes.

Results and Discussion.

Year 4 Focus Group. These students were strongly supportive of the introduction of more enquiry-based lab classes. As well as numerous specific comments, the following comments were made:

- the organic practical units had taught most of the necessary laboratory techniques, but had failed to explain the theory underlying practical techniques;
- the units had reinforced what was taught in lectures;
- the units had not prepared them for their final year projects;
- it was difficult not to treat the given procedures like recipes – there was little thought involved in the process;
- the units gave the expectation that most chemistry works;
- the units did not prepare well for the reality of research (that reactions fail or are low yielding) and initially the students had felt that such disappointing results were their own fault;
- the ideas of prelab assignments and procedures written in journal style were good ones;
- learning of new topics in Chemistry is most effective through practical work;
- the Year 3 labs had been most useful – students carried out reactions unique to themselves, novel compounds were synthesised and they were intimately involved in analysis;
- the transition from undergrad labs to industrial research projects was particularly demanding.

Overall, it seemed that the Warwick experience of lab units in Years 1 and 2 aligned with the literature view of a “traditional” lab class as described earlier. The focus group gave strong support to our initiative and, where possible, the specific points raised by the students (not all listed here) were accommodated in the reinvented unit.

Marks and Feedback. Predictably, examination of average marks from the lab units and the standard feedback forms, which were not designed to capture issues related to preparation for research, revealed little. It did seem, however, that reinvention of the Unit had not had a negative impact on these standard indicators. Representative data follow:

Average marks:

2004 - 63%
2005 - 66%
2006 - 68%

Response to “Given the subject material and the resources available, the course was entirely adequate”:

2004 - agree 93% - no comment 7% - disagree 0%
2005 - agree 94% - no comment 3% - disagree 3%
2006 - agree 92% - no comment 4% - disagree 4%

Full data for response to the standard feedback forms for 2006 are included in the Appendix.

Year 1 Focus Group
Method. Around 13 students (being an alphabetical section of the cohort) were invited to a focus group, of whom five attended. The students were asked to reflect on the Organic Unit and compare it with the Inorganic Unit they were currently taking. Beforehand they had been briefed to think about the following:

- what was the most enjoyable aspect?
- what was the most difficult aspect?
- how does this Unit compare with others you have taken at Warwick?
- how could the Unit be improved?
- what have you learnt about Organic Chemistry that you did not know before the Unit started?
- did the Unit encourage you to undertake research in Organic Chemistry in the future?

Results and Discussion. As well as very many specific points about the Unit that were incorporated where appropriate into the revised handbook, there were a number of general observations of relevance to the wider aims of the proposal.

The points expressed more positively were:

- "the pre-lab assignment was good since it forced you to read the manual before the lab session which is not something you would normally do" - "I understood what I was doing before I turned up."
- the organic manual is easier to understand than the inorganic one
- the procedures are easier to follow than in the inorganic lab
- "it was good to have plenty of time to think about what I was doing"
- the course has encouraged me to read more....
- the half hour between handing in the assignment and the pre-lab
- was a good opportunity to socialise

The points expressed more negatively were:

- a higher level of theory was required for the organic lab
- "the questions at the end of the lab report were very tricky, and required extra reading and lots of thought"
- it was difficult to deal with some of the questions because we hadn't covered the material in lectures

- “the manual didn’t give enough detailed instructions which made doing the experiments quite stressful”
- some of the demonstrators “breezed through the stuff” and the prelab talks were far to brief

These results were extremely pleasing, suggesting that our aim of putting learning through practical experience at the front end of the undergraduate learning experience had largely succeeded. Indeed, most of the negatively expressed comments can be read as positive in the light of the Year 4 students’ reflections on the failure of more traditional classes to prepare them for research.

The most negative comments from any perspective related to the demonstrators and this point will be addressed below.

5.3 Objective 3. To exemplify the possibility of using laboratory classes as primary methods of exposing students to new aspects of theory.

The reinvented classes had several examples of the introduction of theory that had not been covered previously in lectures. The responses quoted in **5.2** above show that the students did note this extra challenge. It is difficult to truly assess the impact of this change, since it would be necessary to talk to the same students later in their course and ask them to reflect on whether it had been easier to study the theory having experienced it practically. At this stage we can say that introducing new theory clearly made the students think and that they did grapple with new concepts, which should benefit them later. However, we would recommend caution in overdoing this, since too much added “stress” in this respect would be likely to detract from some of the other intended learning outcomes.

5.4 Objective 4: To disseminate the experience gained to the rest of the Department, Faculty, Institution and wider HE sector.

This activity has been started and is ongoing.
Department: Year 2 Organic labs reinvented in a similar fashion.
Faculty: Paul Taylor, Mike Neary and Ruth Ayres (CAP) met with colleagues from Biological Sciences to encourage them to apply for funding for similar and related project work (December 2006).
Institution: Presentation to Reinvention Fellows Meeting (Spring 2006).
Wider HE Sector: Presentation to Oxford University Chemistry Department as part of their project to reinvigorate their lab programmes.

6. Outcomes

As detailed in **5.,** a protocol has been developed that can readily and cheaply be adapted for reinvention of laboratory classes in a range of disciplines and contexts, with the aim of creating a more research-like environment. The protocol has been applied successfully to undergraduate Organic Chemistry lab classes at Warwick and the ideas have been and will continue to be promoted to the wider community through presentations to other Departments, both at Warwick

and elsewhere, and to meetings organised, for example, by the HEA Subject Centres.
A further outcome is the profound effect on the personal development of both Paul Taylor and Jo Geden, which will have a significant impact on their professional careers.

7. Resources
Lab manuals for year 1 and Year 2 organic Chemistry courses are attached.

8. References

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