

COMMUNITY DIRECTIONS

From Cook to Chef: Facilitating the Transition from Recipe-driven to Open-ended Research-based Undergraduate Chemistry Lab Activities

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Abstract

This paper describes the development of mini-research projects in the third year practical chemistry course at the University of Nottingham for the MSci(Hons) Chemistry degree. The aim of these developments is to bridge the gap between 'recipe-style' experiments in the first and second year courses and research projects undertaken in the fourth year or in industry. There is much evidence that, having been given this opportunity to plan and design their own experiment, students exhibit higher-order cognitive skills, which can lead to a more valuable learning experience.

Keywords: mini-projects, practical skills, team working, transferrable skills, research, inquiry

Introduction

During the course of an MSci/MChem four-year Chemistry degree we expect students to acquire a diverse set of practical skills, such that by the end of their fourth-year research project a student is able to carry out research semi-independently and communicate the methods and results effectively. Until recently the practical courses at the University of Nottingham consisted of 'recipe-style' experiments in teaching laboratories in Years 1–3 that covered essential synthetic and analytical techniques followed by a 20-week research project embedded within a research group in Year 4. The contrast between expectations and task demands

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placed on students between these two styles of laboratory meant that students often found the transition between third and fourth year labs difficult. Many students lacked the underpinning skills of teamwork and the ability to plan and work independently that are necessary to be effective and successful in a research group environment. Over the past few years we have developed mini-research projects for all Year 3 students, with the aim of bridging this gap between 'recipe-style' practicals and a more independent research-focused practical.

Recipe-style experiments still have an important role to play in the education of undergraduates, in particular to allow them to acquire basic experimental skills and techniques as well as the confidence and ability to function safely within a laboratory environment; Johnstone & Al-Shuaili (2001) stated that "real enquiry can only come after certain knowledge of facts and practical methods has been gained." Once students have achieved a broad foundation in the practical skills that underpin chemistry, it is then important to further develop these skills: as Jennifer Lewis (2002) stated in her case study: "there is a clear need for some form of laboratory work which can help undergraduate students to make the transition from set practicals that are designed to develop their technical skills to open ended investigations designed to develop their research skills." Whilst managing the transition from recipe-style experiments to open-ended investigations in which students plan and conduct laboratory work with a significant degree of independence, it is also necessary to ensure they are able to cope with a considerably reduced experiment 'success' rate and with data that are less 'clear-cut' and hence more difficult to interpret.

Different laboratory styles

Practical activities can be grouped into four distinct styles: expository, inquiry, discovery and problem-based, as described by Domin (1999). These styles, in turn, can be differentiated by three descriptors: outcome, approach and procedure (Table 1).

Johnstone & Al-Shuaili (2001) discussed these styles extensively and concluded that 'recipe-style' experiments fall into the category of 'Expository Instruction' and final year research projects fall into the category of 'Open Inquiry.' Expository instruction is the most common type of practical and involves the learner following a detailed procedure from a laboratory manual for which the outcome is predetermined. This type of practical gives very little opportunity for students to plan an experiment. At the opposite end of the spectrum inquiry-based activities have an undetermined outcome and require an inductive approach; they are student-centred, with the students taking responsibility for the design and direction of the project, and determining the procedures they will adopt. Such approaches have been found to be successful in other universities; some examples include those reported by Kelly & Finlayson (2007), McDonnell *et al.* (2007) and Limoto & Frederick (2011). The benefits of engaging the students in this way are multi-faceted: by allowing students to take ownership for the design of their laboratory project they are likely to be more motivated and engaged in the project and as a consequence, more interested. There is also evidence that inquiry-centred activities promote the use of higher-order cognitive skills. Bodner (1986) noted that "the constructivist theory of knowledge states that knowledge cannot be transferred from one person to another; it must be actively constructed by the learner through interactions with the environment." Raths lists the following higher-order thinking processes as components of inquiry: hypothesising, explaining, criticising, analysing, judging evidence, inventing and evaluating arguments (Raths *et al.* 1986). These are all skills we value in good research chemists, but they are also transferable and potentially applicable to a much wider range of activities (Bennett & O'Neale 1998). In addition, a skills development project run by Hanson & Overton (2010) highlighted the skills deficits among Chemistry graduates: among the top ten were deficits in experiment design, team working, oral presentations and time-management. It was this skills deficit, and consideration of the potential gains of introducing project work highlighted above, that informed the direction for

Table 1 Descriptors of laboratory instruction styles.

Style	Descriptor		
	Outcome	Approach	Procedure
Expository	Predetermined	Deductive	Given
Inquiry	Undetermined	Inductive	Student generated
Discovery	Predetermined	Inductive	Given
Problem-based	Predetermined	Deductive	Student generated

the redevelopment of our third year practical course.

Discussion

The practical course at Nottingham, as in many other university Chemistry departments, is divided into three separate laboratories, inorganic, organic and physical chemistry. Students carry out a mini-project in each of these labs over the course of their third year, each project running for 10 hours a week for five weeks. We have designed the projects such that the focus is a more guided inquiry rather than a completely open-ended inquiry. The reason for this approach is that, given a limited time in each lab, we need to ensure that all chemicals and equipment are available for students to use. Students are provided with a list of available chemicals and equipment and then are able to design their projects within this context. A pure research project that could be undertaken in a research laboratory where there is the possibility to order whatever chemicals are required, and to have access to a wider range of equipment, would be categorised as pure 'open inquiry'. Within our directed inquiry approach there is an opportunity for students to suggest alternative methods and reactions within the introduction and future work sections of their reports and presentations. During the laboratory time an academic demonstrator and a number of post-graduate demonstrators are available, including one allocated to the project, who can give more in-depth guidance on most aspects relating to it. The project supervisors (academic staff) provide support at various times in the lab during the week both during lab visits, being present for one three-hour lab session per week, and through meetings and email correspondence outside of lab hours.

Transferable skills

Integrated into the third year practical module are sessions on transferable skills that occur at the start of the academic year before the projects commence. These sessions concentrate on the skills required to search the literature, write scientific reports and give oral presentations. The sessions build on those experiences students have gained in their first and second years and provide valuable information and guidance for the transferable skills elements of the projects.

Week 1

In the first week of each laboratory rotation students receive an introduction to the particular laboratory to which they have been allocated and are given a brief outline of the project. The teams work together to search the literature and devise a

project plan to address the problem posed. In inorganic and organic chemistry students work in teams of between four and six, while in physical chemistry they work in teams of three. Each project group has an academic supervisor who supports them through this process. At the end of the first week the project supervisor ensures that the students' proposed project plan is viable, this summary (proposal) being worth 10% of the final project mark. After the first week the physical chemistry lab is organised in a slightly different way from the organic and inorganic labs (see below).

Weeks 2–4 – Practical work

In the second week students in inorganic and organic chemistry write COSHH (Control of Substances Hazardous to Health) and risk assessments for their experiments. Once these have been approved by their academic supervisors, they commence their planned experimental work. Students are expected to distribute the work within the team to ensure they make most efficient use of the laboratory time; how they do this will of course vary from project to project. The practical element continues for three weeks during which time students continually modify their original plan through team discussions, as appropriate, depending on the results they have obtained at that time. The project supervisor assesses each student's contribution to the project by considering the quality of the chemistry performed, together with their engagement, and awards a mark that is worth 40% of the overall project, broken down into a number of smaller elements.

Week 5 – Report and oral presentation

At the end of the project, students are required to write an individual report in the style of a scientific paper; this should be no longer than six pages and is worth 40%. During the fifth week students are also required to give an oral presentation, each group member speaking for 5 minutes as part of a group presentation. At the end of the presentation opportunities are provided for questions from their peers and the academics present; this presentation is worth a further 10% of the overall mark. By ensuring that all assessment associated with each lab is contained within the five-week session, students can concentrate fully on their current task, without concerns of overlap with the next project.

Physical Chemistry

During the first year of the new course we ran the projects in physical chemistry using the same format as the other two labs as described above. However, because of the different nature of the projects in physical chemistry, and the prominence of data handling, during the last academic year we

took the decision to make a number of changes to the methodology. In the second week, instead of the students starting their practical work, they now give a presentation on their proposed project plan and carry out a series of data handling exercises. The rationale for this is that they will then start their practical work with a more informed understanding of the science and the essential data manipulation skills. The practical work is then completed in the third, fourth and fifth weeks.

One of the many positive aspects of this new course is that students go through three iterations during the year, with the quality of the literature searching, report writing and presentations increasing noticeably over the year in spite of the stylistic differences between the labs. For this to be effective, an essential element is that students receive comprehensive feedback after each rotation and the opportunity to reflect on this prior to the next laboratory. The iterative series of presentations the students have to make provides an opportunity to build the students' confidence in this important skill.

Project topics

The project topics are wide-ranging across all areas of chemistry, some examples include:

- investigation into the factors that affect the yield and quality of metal organic frameworks (MOFs);
- effect of substituents at π -bonded aromatic fragments on the electronic structure and bonding reactions of organometallic chromium complexes;
- ionic liquid synthesis *via* ion metathesis reactions of protic piperidinium cationic species;
- electronic structure computation of periodic solid state materials;
- kinetic study of the thermal *cis-trans* isomerisation of a substituted azobenzene in polar and non-polar organic solvents;
- mass spectrometry of selected organic compounds and determination of thermodynamic properties of phenol using temperature programmed desorption;
- investigation into alternative catalysts for the formation of 1,2,3-triazole with the use of Click Chemistry;
- investigation into how different palladium catalysts affect the Suzuki reaction.

Student feedback and evaluation

At the end of the academic year, Year 3 students were asked a range of questions about the projects

as part of the university's Student Evaluation of Module process and asked to respond using a 5 point Likert Scale:

- 91% of students agreed or strongly agreed with the statement: "I enjoyed the projects more than 'traditional' labs"
- 85% of students agreed or strongly agreed that "having the opportunity to do three presentations improved my presentation skills"
- 76% of students agreed that "I feel confident writing a scientific report"
- 82% of students agreed or strongly agreed that "I feel confident searching the chemical literature."

The following are quotes from students, taken from the same evaluation questionnaire, when asked:

"What did you like about the mini projects?"

"We had a lot of interaction with our group leader but we still worked independently."

"The opportunity for teamwork and independent learning and to do something new was valuable."

"The chance to study the literature and design my own project with the group."

"Had to use our initiative."

"It was interesting to devise an experiment and carry it out."

"The projects gave me the opportunity to put academic science into real world context."

"One can take more responsibility for the experiments – this also requires you to be more confident and knowledgeable about the chemistry used."

"More relevant to scientific research."

"It has really triggered my interest in crystallography."

"Freedom to organise our own time."

"True experiments rather than following a set recipe."

"If it went wrong I felt confident that figuring out why it was wrong was worth more than having good luck in the experiment."

"The ability to choose the direction in which the project went."

"It's really tough but great fun."

"I learnt more than 'traditional' labs because of the emphasis on having to think more."

Towards the end of the academic year fourth year students were asked to reflect on their experiences

of the transition from second to fourth year and whether the third year lab projects had facilitated this transition effectively. The responses were very positive, quotes from students included:

"The third year projects gave an insight into what to expect in the fourth year research project. Skills developed include ability to work effectively in a team, effective time management, ability to present work in a variety of different formats and the ability to adapt when an experiment gives an unexpected outcome."

"Recipe style would have given me more time in a lab which would have been better, but having a project and having to work on it was much more like 4th year. Literature surveys were really helpful in learning to find papers, the presentations were also really helpful – I'm glad we were made to give presentations, it's good practice."

"Yes- looking back the third year projects meant that I got a lot more out of my fourth year project than I may have otherwise done. For me, the third year projects were one of the highlights of third year!"

Conclusions

The introduction of mini-projects into the third year practical course for Chemistry required a major investment, in terms of both staff time and resources, but this has been a very worthwhile investment. The majority of students engage extremely well and enjoy the course. Evidence from the questionnaires and regular dialogue with students in the lab over the past few years suggests that we are succeeding in improving student engagement, whilst also increasing the number of transferable skills which students develop and that are essential for graduate chemists. The responses above are testament to the success of the new course structure and experience. Fourth year students stated that they developed valuable

transferable skills during the third year practical course, which prepared them well for fourth year research projects. The structuring of the third year practical course into three mini-projects was also noted as beneficial; having three opportunities to write project reports and give presentations allowed for effective feedback. Some students commented that the projects were not long enough and this is something we shall consider when planning for future years.

Our aim was to try and improve the transition from recipe-style experiments in the second year to research in the fourth year. In addressing this, we have, however, created a similar gap in student experience between the second and third years. Over the next couple of years we will be reviewing the first and second year courses with a view to integrating more inquiry-based learning throughout the whole of the practical course.

As with any change, our approach to and integration of mini-projects highlight further areas for improvement. One particular area that we are looking to improve for the academic year 2014–15 is the feedback loop, to ensure that students gain as much as possible from the feedback from each lab and that they then apply this in their next laboratory session. We are also looking to further develop the transferable skills sessions in the second week with a view to improving students' report writing skills close to the start of the year.

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