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Introducing elements of inquiry in to undergraduate chemistry laboratories

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Inquiry-based laboratories are an emerging and popular way of teaching practical chemistry. They lead students towards independent research by inspiring critical thinking, curiosity, and a conceptual understanding of experimental processes. Inquiry laboratories need a base of knowledge, usually built upon a foundation of expository experiments that teach fundamental skills. As such, the first year of a teaching laboratory may well keep an expository structure, even when later years embrace inquiry learning.

In this work, we have shown that elements of inquiry can be introduced lightly and early in the curriculum, using the approach of Szalay and Tóth. In this work, a robust suite of existing experiments has had elements of inquiry introduced with a series of small, standalone modifications. Adaptation of existing experiments allows a tight control on the extent to which a student pushes into unfamiliar territory — particularly important for introductory laboratories, where unexpected results are likely to overwhelm or discourage. The modified experiments confer many of the same benefits as an inquiry laboratory, such as students' sense of independence and control. The approach works best when supported by pre-laboratory exercises, for calculations or procedure-writing steps.

The approach builds on prior work introducing inquiry into a school curriculum, and we have shown that it can be used on a large scale in two different undergraduate teaching laboratory environments. In our implementation, we placed a heavy focus on structured support for students, and conducted numerical and written surveys of students and postgraduate demonstrators to measure perceptions of the work.

Influence of Professor Tina Overton (Patrick Thomson)

Tina was instrumental in creating, and in continuing to shape, the UK chemistry higher education landscape. Her work bringing context-based and problem-based learning to chemistry, and acting as a wider advocate and trailblazer for chemical education, are the reasons my vocation and my professional identity exist. This work would not be possible without the community she fostered, who reflect her values in the welcome they give me and other newcomers.

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Introduction

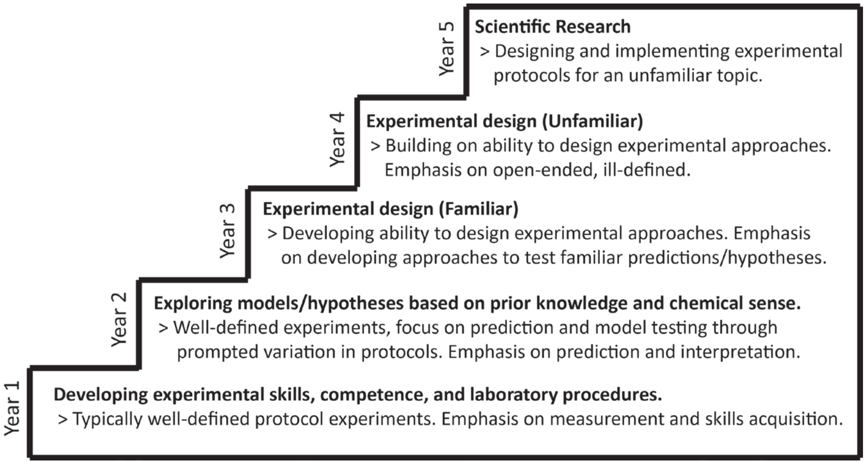
The teaching laboratory is a distinctive feature of chemistry education, described as our "signature pedagogy" (Shulman, 2005). Like the lecture, the teaching laboratory had remained relatively unchanged from the advent of the discipline until the late 20th century; Berzelius or Curie would find little different in most chemistry departments even relatively recently.

The core, and sometimes only, component of a teaching laboratory is the experiment: a self-contained practical procedure designed to illustrate some principle, show some reaction, teach some technique, and generate some data — all in a few hours. Although we call them experiments, they are more akin to recipes: a series of steps, specified quantities of ingredients, a proscribed process, and a known output. Generating this output in the desired quantity and quality is taken as a sign that learning has happened.

This traditional approach to laboratory education is referred to as the recipe-based or expository experiment — and has settled into dominance for many pragmatic reasons. Expository experiments are scalable and reliable: a few instructors can lead many students without unexpected twists and turns. They are robust: execute the recipe with reasonable competence, and get the expected result. Robustness arises over time, so it can be difficult to justify scrapping something that works. Robust experiments rarely go wrong, minimising headaches for those running the laboratory and stress for our students. And they serve to efficiently train students in many of the actions of practical chemistry.

When we ask whether expository laboratories teach chemical theory or experimental design, though, the response can be weaker. It is likely that a student could follow a recipe without thinking about what they were doing, while they were doing it. This failure to achieve meaningful learning happens for a number of reasons, such as the desire to finish early — a desire we can be complicit in as instructors (DeKorver and Towns, 2015).

To address this shortcoming, several innovative approaches to practical instruction have emerged in the last few decades of chemistry education research, such as discovery, inquiry, or problem-based learning (Domin, 1999, Kelly and Finlayson, 2007, Mc Donnell *et al*., 2007). Recently, Seery and co-workers published a framework for learning in the laboratory, with a focus on experimental design — laying out a progression towards independent research ability (Seery *et al*., 2019). Their framework (Figure 1) does not



Scientific Research
> Designing and implementing experimental protocols for an unfamiliar topic.

Experimental design (Unfamiliar)
> Building on ability to design experimental approaches. Emphasis on open-ended, ill-defined.

Experimental design (Familiar)
> Developing ability to design experimental approaches. Emphasis on developing approaches to test familiar predictions/hypotheses.

Exploring models/hypotheses based on prior knowledge and chemical sense.
> Well-defined experiments, focus on prediction and model testing through prompted variation in protocols. Emphasis on prediction and interpretation.

Developing experimental skills, competence, and laboratory procedures.
> Typically well-defined protocol experiments. Emphasis on measurement and skills acquisition.

Figure 1: Seery model for experimental design skills development (Seery *et al.*, 2019, reproduced with permission)

prescribe one particular approach, but serves as a roadmap for the structured introduction of discovery, inquiry, or problem-based learning elements into a laboratory course.

Within the inquiry approach, guided inquiry sits as a useful intermediate between authentic scientific inquiry and inquiry-free exposition (Fay *et al*., 2007, Buck *et al*., 2008). Guided inquiry laboratories are an emerging and popular way of teaching practical chemistry, and lead students towards independent research by inspiring critical thinking, curiosity, and a conceptual understanding of experimental processes (Mistry *et al*., 2016).

Guided inquiry laboratories address a common critique of expository labs: following a recipe leaves little room for higher-order skills development, giving a jarring transition from novice to expert chemist in later years of degree study (Figure 2, left) (DeKorver and Towns, 2015). Although a teaching sequence will increase the complexity of the tasks being performed, or the complexity of the underlying chemical theory, the same progression is often not seen in skills such as experimental design or theoretical-practical linkages as advocated by Seery (Figure 1).

Guided inquiry laboratories require a foundation of practical knowledge, usually built on a diet of expository recipes designed to teach basic practical skills. Hence, the first year of a teaching laboratory often retains an expository style, (Figure 2, middle) even when subsequent years embrace inquiry learning (Fay *et al*., 2007, George-Williams *et al*., 2018, Buck *et al*., 2008). This can then give rise to a difficult transition when students encounter inquiry learning for the first time. There has been some prior work on supporting this transition in a general higher education context (Edelson *et al*., 1999), and in writing methods for guided inquiry chemistry laboratories (Van Duzor, 2016).

In this chapter, we argue that elements of inquiry can be introduced early in a university curriculum, within existing expository experiments (Figure 2, right) (Szalay and Toth, 2016). Szalay and Tóth showed that guided inquiry experiments could be adapted from existing expository experiments taught in secondary schools. They further demonstrated that these guided inquiry experiments would confer many of the same benefits as a fuller inquiry-based curriculum, even if only used a few times in an academic year. We were encouraged by this work and applied it to a first-year university teaching laboratory. The approach of adapting existing expository experiments to add layers of inquiry has recently been used to great effect on more advanced subject material by Seery in an upper-division physical chemistry laboratory (Seery *et al*., 2019a). The following serves as a practical guide to adapting existing expository experiments into elements of inquiry experiments, using our own work as case studies and documenting our approach for others to follow.

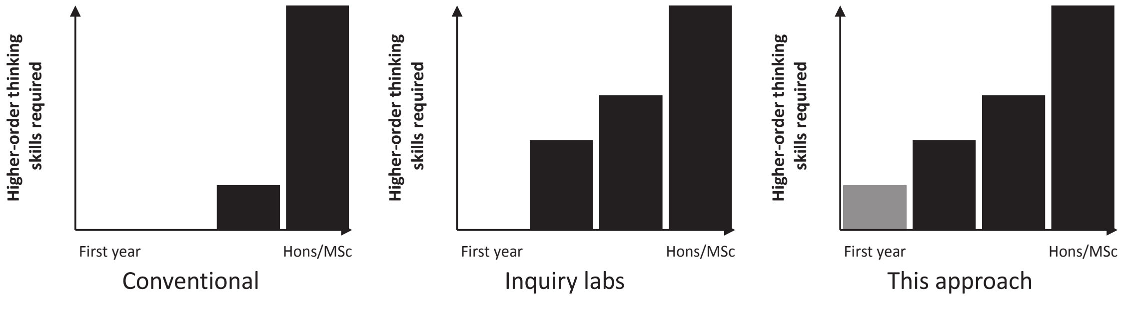


Figure 2: A comparison of higher-order thinking skills development in laboratory sequences through the course of an undergraduate degree

Methods and Design

The implementation of our teaching approach followed a consistent pattern. Firstly, we selected a laboratory procedure; either a newly-created or an existing expository experiment. Secondly, we identified places where elements of inquiry could be added. Thirdly, we wrote or rewrote the experiments to include elements of inquiry. Lastly, we deployed them within an existing course structure and conducted evaluations. This was employed in two separate practical courses in two separate contexts (Table 1). One new experiment on the topic of soap making was newly-created, with elements of inquiry included in the design from the beginning. The experiment was then evaluated with a pilot group of volunteers. After positive feedback, the experiment was deployed for all participants of a pre-entry summer school from 2017 onwards and also disseminated via a secondary school CPD event. Our approach was then introduced into a first year undergraduate teaching laboratory, where some existing expository experiments were adapted to contain elements of inquiry and redeployed into the laboratory course.

Table 1: Summary of new and adapted experiments, deployed in two different laboratory courses over three years

Experiment topic	New or adapted?	Student level
Soap making	New	Pre-entry
Double salt synthesis	Adapted	Year 1
Electrolyte conductivity	Adapted	Year 1

Setting and Scope

The first course chosen for modification was the laboratory portion of a pre-entry summer school. About 20 students each year take this course, who have been made a conditional offer of undergraduate study. Every student takes the same experiment at a pre-determined time and so laboratories are closely linked to lecture material.

The second course chosen for modification was a first year undergraduate teaching laboratory. Like many other institutions, this laboratory serves a large number of students for a single practical teaching session each week, with up to 250 students across four sessions. Students attend the laboratory for a single 3-hour long session each week for 16 weeks across two semesters. Due to equipment limitations the experiments follow a rota, so there is limited scope for dependent sequences or lecture tie-in. Each week, students conduct a short pre-laboratory exercise before attending, and complete a laboratory report or worksheet after attending. Pre-laboratory exercises are a key component of supporting and extending laboratory work and are another major quick win which can be slotted in to an existing laboratory course (Agustian and Seery, 2017).

Uptake of pre-laboratory activities in our laboratory courses are near-universal for a number of reasons. Pre-laboratories are given a mark weighting, providing a strong incentive for student engagement. Time is spent at the start of the year laboratory induction on the value of pre-laboratory activities for preparation — saving the student time overall. Pre-laboratory questions are only available the week before the experiment, so they are fresh in mind. Lastly, staff and demonstrators make frequent in-laboratory references back to pre-laboratory activities. For both laboratory courses (Year 1 and pre-entry) the experimental rota consisted of well-worn expository experiments, loosely aligned to lecture content. The experiments covered a full range of the chemistry curriculum, although each individual experiment had a distinct flavour that aligned with synthetic, analytical, or physical chemistry.

Elements of inquiry

The inspiration for this approach came from work on introductory guided inquiry in the Hungarian secondary school curriculum (Szalay and Toth, 2016). In this study, pupils ran an initial expository experiment into chemical kinetics, then were asked to run repeated modifications of the procedure to investigate a given hypothesis. This worked because the initial experiment was short, repeatable, and amenable to modification.

What we have attempted to do in our approach is to build on this work, bringing it into tertiary education and applying it to laboratory procedures that do not have the same structure of component repetition. We have done this by adding elements of inquiry. These are small, self-contained modifications to pre-laboratory, in-laboratory, or post-laboratory work. The modifications we have deployed so far are shown in Table 2, along with a brief description and where in the laboratory sequence they are used. Developing these modifications required a careful consideration of student time constraints, with additional time being freed up in some cases by moving calculations to out-of-laboratory activities.

Example elements of inquiry

One experiment on the topic of soap making contains two main elements: *calculate reagent quantities* and *unscramble procedure*. In the first element, students are asked to calculate quantities of reagents for making a bar of soap (Figure 3) having previously completed a short pre-laboratory exercise as a refresher on esters and ester chemistry. This first element is purely calculation-based and could be delivered as a pre-laboratory exercise, but students benefitted from having access to peers and demonstrators while working on the problems. When students had calculated all the quantities, they then inserted them into blanks in a scrambled procedure (Table 3). For the second element, students descrambled this procedure and followed it to make a bar of soap.

Table 2: Examples of elements of inquiry

Modification	Brief description	Location in laboratory sequence (pre/during/ post-lab)?
Calculate reagent quantities	Exploration of stoichiometry, volume, and concentration.	Pre/During
Unscramble procedure	The procedure is given as a scrambled list, and students need to unscramble before following it.	Pre/During
How many data points?	Students are asked to define the number of measurements they make.	During
Selection of reagents	Students are asked to make a judgement about e.g. the suitability of distilled *vs.* tap water for analytical measurements.	During
Create your own synthesis	Students are asked to write their own procedure, using only combinations of prior techniques.	Pre/During
Create your own analysis	Students are asked to write a balanced equation, determine stoichiometry and concentration, and conduct an analytical titration with appropriate volumes of titrant and titrand.	During/Post

Task 1: You want to make a 20 gram bar of soap, and you find a simple soap-making guide that suggests a good blend of oils would be 70% by weight of sunflower oil, and 30% by weight of coconut oil. How much of each oil would you need?
Sunflower oil: ___ grams **Coconut oil: ___ grams**

Task 2: Each oil has a different saponification value (see the table on the previous page). What are the saponification values of the oils you are using, when saponified with the base NaOH?
Sunflower oil: ______ **Coconut oil: ______**

Task 3: If the saponification value is the number of grams of base needed to react completely with each gram of oil, then how much base do you need to react with each of the quantities of oils calculated in step 1?
NaOH needed for ___ grams of sunflower oil: ___ grams
NaOH needed for ___ grams of coconut oil: ___ grams
Total NaOH needed for complete saponification: ___ grams

Task 4: In practice, bars of soap are not made with an exact balance of oils and base, since any slight excess of base would make soap unusable. Soaps are usually made with a slight deficit of 5% of the total amount of base. Reduce the amount of base you calculated in step 4 by 5%.
Total NaOH used to make a usable bar of soap: ___ grams

Task 5: The NaOH you are using is in the form of a 6 molar solution. What volume of this solution do you need to use? You will need to calculate the number of moles required first, and use the molecular weight you calculated in the pre-lab to finish the calculation.
Total moles of NaOH to be used: ___ moles
Total volume of 6M NaOH to be used: ___ mL

Task 6: Get all of your answers checked by a demonstrator before going to the next page.

Figure 3: example of the *calculate reagent quantities* element as used in a soap-making experiment

In another example, an existing expository recipe for the preparation of ammonium iron(II) sulfate was replaced with two new tasks: balance the overall equation for the reaction and a *create your own analysis* task (Figure 4). The given list of hints are a consequence of the need to present students with an achievable challenge. Each hint addresses something that would be possible for a student to determine experimentally or by literature search, but this would result in a variable or overwhelming experience that would take longer than one laboratory session and potentially operate at a much higher level of inquiry than intended. The second half of the experiment then uses *create your own analysis* by presenting the students with a set of unbalanced redox half-equations for an appropriate titration, and asking them to write an analytical procedure similar to one they have previously conducted. This entire sequence could be more ambitious as it came in the second semester, after students had all completed a first semester that introduced recrystallisation and titration analysis. Further examples of elements of inquiry in practice can be seen in the Supplementary Information, with a full comparison of expository and reworked laboratory manuals, demonstrator manuals, and student post-laboratory outputs.

Compared to even the lighter aspects of guided inquiry, these elements do not seem like major modifications: for example, *unscramble procedure* requires only that students use some logical guesswork about reasonable sequences of events. Students converge on a correct expository sequence, which they

Table 3: *Unscramble procedure* from Study 1, synthesis of soap — students had to sort the steps in order, after filling in quantities of reagents calculated in a previous step

Step Number	Brief description
	Grease two weighing boats by wiping with some sunflower oil on a piece of paper towel. Pour the contents of the beaker equally into these two boats and leave them on your bench overnight to finish reacting. A demonstrator will put them safely aside until the next experiment that uses them.
	Measure out ___ grams of solid coconut oil on a watch glass and add all of it to the sunflower oil in the beaker.
	Stir the mixture with a PLASTIC spatula for 15 minutes, or until the mixture begins to thicken. Be sure to stir the mixture without splashing.
	Using a 10 ml graduated pipette, carefully, measure ___ mL of the stock 6 molar NaOH, and add it to the beaker containing your oil. (This step MUST be done in the fume hood).
	Gently heat the beaker of oils on a hotplate set to 50 °C, in order to melt them.
	Into a 100 ml beaker, weigh out ___ grams of sunflower oil (this is a liquid, so do not weigh it directly over the balance.)

then follow as normal. A major aim of the work, though, is to give students a sense of challenge and control whilst retaining the reliability of an existing experimental sequence, and this has been successful. The approach is also adaptable to different teaching laboratory settings. In our implementation, two separate laboratory courses were used, both of which consisted of 3-hour long single sessions. However, the soap making experiment has been presented as 1.5-hour long teacher CPD session, and elements of inquiry could easily be introduced to shorter or longer sequences.

Original expository procedure

Dissolve 5g of iron(II) sulfate in 12.5cm^3 (do not use more than this) of dilute (bench) sulfuric acid. Add 5g of ammonium sulfate and heat until it all dissolves. Cool in an ice bath. Filter off the pale green crystals on a Buchner funnel. Draw air through the crystals until dry (about 15 mins). Finally, dry the crystals by pressing between filter papers. Weigh and calculate the yield based on the weight of iron(II) sulfate used. Retain a sample for inspection.

Adapted elements of Inquiry procedure

Ammonium Iron (II) Sulfate Hexahydrate can be prepared using only techniques you have already used in semester 1. Using the balanced reaction formula, and existing techniques, write an experimental procedure for preparing approximately 5 grams of this compound. Your procedure should incorporate the following pieces of information and previous experimental findings. Consider each one carefully.

- *As the reaction solvent, use bench dilute (1 molar) sulfuric acid.*
- *You should use no more than 12.5 cm^3 of this reaction solvent.*
- *The starting materials should be fully dissolved in the reaction solvent. Hint: what technique have you previously used to fully dissolve crystals?*

The yield is substantially higher if two molar equivalents of ammonium sulfate are used.

Figure 4: Original versus adapted procedure for mixed salt synthesis; the adapted procedure is also supported by a short section of theoretical background that points students towards the need to use a recrystallisation-like procedure, in this case, heating (see Supplementary Information for details)

Assessment

For the new experiment on soap making, assessment was based on successful calculations followed by a successful unscrambling of the procedure prior to the start of experimental work (see Supplementary Information for student manuals and marking schemes). The quality of the product was assessed in a separate expository experiment, where the soap was assayed for solidity and pH after curing for several weeks. For the adapted experiments, post-laboratory assessments largely followed the existing criteria which judged yield and purity to determine success. For example, when synthesising a sample, 80% of the marks come from sample yield and purity as with existing criteria, 10% from calculations, and the final 10% from a pre-laboratory exercise.

We were reluctant to include elements of in-laboratory assessment at the same time as an entirely new approach, so some elements of inquiry that happened during a laboratory sequence were not assessed directly. For example, when students wrote a synthetic procedure, this was checked by a demonstrator before the students progressed. The procedure itself was not assessed, so that we had the ability to correct it on-the-fly to ensure students had successful experiment and a positive overall experience.

Training of demonstrators

Laboratory teaching at our institution is supported by a team of demonstrators, and much has been written about the importance of their training for non-expository laboratories (Wheeler *et al*., 2017a; Flaherty *et al*., 2017; Wheeler *et al*., 2017b). We provided specific support for this new style of experiments within the existing demonstrator handbooks (see Supplementary Information). An important aspect here was providing reassurance to demonstrators that their students would not be overwhelmed, as we observed a strong pastoral impulse to provide detailed hands-on coaching in the face of a new style of challenge. This may come from our demonstrators' own recent experience of a sharp transition into a research environment.

Ethical considerations

Initially, student volunteers were recruited for a closed pilot run of new experimental procedures, with no academic credit or financial compensation. In all cases, ethical approval was granted by a departmental ethics board. Subsequent modified experiments were deployed directly into the curriculum. This could be justified for a number of reasons:

- Changes to the laboratory based on literature precedent routinely happen without piloting.
- The pilot group reported none of the negatives which have been previously observed with non-expository laboratories and inquiry learning (Wheeler *et al*., 2017b; Flaherty *et al*., 2017; Dunlap and Martin, 2012; Edelson *et al*., 1999).
- The principal and co-investigators were present in the laboratory during the study to intervene if students encountered unexpected difficulties.
- There was enough precedent in later iterations for a neutral or positive outcome that depriving a control group of the intervention was difficult to justify.

Presentation and Discussion of Findings

Each iteration of our approach was supported by qualitative and quantitative survey data. For each new or modified experiment, a student would follow the elements of inquiry procedure, then fill out a short survey. For some of the experiments, we also surveyed the demonstrators who were responsible for delivery of the teaching materials. Detailed survey results can be found in the Supplementary Information.

Student feedback

The development of our approach was supported and guided by student survey feedback, taken either from volunteers who were piloting experiments, or from students conducting one of the modified procedures as part of the mainstream curriculum. Across all surveys, we found a consistent theme of an increased sense of freedom, both quantitatively in numerical responses, and qualitatively in free-text comments. Even as first year undergraduates, participants were keenly aware of the gulf between expository experiments and the world of graduate chemistry, for example one student reported that:

> *after my degree I won't work using recipe based experiments […] guided inquiry experiments help understand the reasons behind volumes/concentrate/other parameters used in an experiment.*

A substantial number of students also positively commented on increased independence and the requirement to think more, a situation that continues to be evident in informal in-laboratory observations in subsequent years. The role of positive experience, the affective domain of learning, is an increasingly prominent part of practical education in chemistry (Galloway *et al*., 2016) and we placed high importance on affective characteristics.

Tutor and demonstrator feedback

Students in our laboratories are led closely by a single demonstrator; the same person each week. Because of this structure, demonstrators often develop a close rapport with their students, and are valuable contributors to the continual cycle of laboratory enhancement. However, most of our demonstrators had previously earned an undergraduate degree in the same institution, and so had become accustomed to a culture of expository experiments. As such, demonstrator feedback is a big part of developing robust recipes but can sometimes view student challenge as a negative rather than an opportunity for learning.

Demonstrators were qualitatively surveyed about their perceptions of elements of inquiry before and after delivering them to their groups of students. Pre-delivery, most respondents were concerned that students wouldn't be able to cope with the independent thinking required, but this changed after having seen the students actually go through the work. This highlighted the need to give specialist guided-inquiry training and support to demonstrators.

New versus adapted

Initially, one new experiment was created from scratch to fill a gap in the curriculum of our pre-entry summer school (Table 1). Soap making was used to explore the concepts of stoichiometry, esters, concentration, and pH. An initial expository preparation was created from hobbyist recipes, then elements of inquiry were added. The process of adding elements of inquiry was so rapid and convenient that it served to lay the groundwork for the next iteration of the approach, namely adaptation of existing recipes. The experiments we adapted the following year were chosen partly for pragmatic reasons: those particular experimental sequences were shorter, with students routinely finishing over an hour early. The experiments consisted of an expository sequence to follow, with post-laboratory exercises focusing on the analysis of data or yield and purity calculations. Elements of inquiry were added quickly, replacing given procedures with pre- or in-laboratory calculations.

We found that adaptation was quicker and more efficient than creation, with two adapted experiments (and associated evaluations) taking the same time as one newly-created. The time saving was mostly due to using a robust existing procedure, whereas creation required several design iterations to arrive at a reliable procedure to start from.

Limitations and future improvements

One important drawback we identified early was the use of in-laboratory time on non-laboratory activities. One of the experiments was assessed on the day by a fill-in-the-blanks worksheet (see Supplementary Information), and some students struggled to complete this by the end of the session. This experiment also required students to work out parameters for an analysis of their product, and this delayed the onset of the analysis itself. The experiment in question was a candidate for modification as it was usually completed 90 minutes early, and all of this extra time was consumed by the new approach. In a subsequent iteration of the design, calculations were supported by an additional pre-laboratory question and this has alleviated the time pressure on the experiment itself.

One of the pilot studies used volunteer students who undertook an additional laboratory session, unrewarded, so were not indicative of the typical student. The pilot study was used to test novel chemistry, but we overlooked the potential for a pilot to also identify issues with student write-ups. When subsequent adapted experiments were deployed directly into a live laboratory rota, we quickly identified issues with time spent on calculations, and this awareness could have come from pilot groups instead.

Implications and Adaptability

The following serves as points to consider if you wish to introduce elements of inquiry into your own teaching, following the approach we have described in this chapter so far.

Choice of laboratory course

Our approach was deployed into a course right at the outset of a chemistry degree, and benefitted from lack of prior student expectation (Shulman, 2005). Year 1 is an ideal opportunity to establish the tone of an educational environment, however implementation into a later year would work if your students have studied a purely expository sequence up to that point.

Interaction with other laboratory courses

The approach is designed to introduce inquiry elements into an entry-level laboratory course. This would be ideally suited to support a transition into existing mid- and upper-level courses that use inquiry, discovery, or problem-based learning. The approach benefits from close interaction with the heads of these laboratory courses. However, elements of inquiry can also serve as a driving force for innovation in later years, as has been seen starting to happen in our institution.

Staff and demonstrator buy-in

In your laboratory, the day-to-day teaching may be facilitated by other staff members and/or postgraduate demonstrators. They may be reluctant to move away from expository teaching, and elements of inquiry may serve as a gentle introduction to alternative ways of teaching practical chemistry. We found that our demonstrators' own recent transition from recipe laboratories into authentic research provided ample buy-in and they became valuable contributors in their own right.

Students as partners/researchers

All of the survey work and a large portion of procedure writing were conducted by two masters project students, co-authors of this work and instrumental in bringing it to fruition. We also relied on volunteer first year undergraduates to pilot one of the new experiments, and their unique perspectives further shaped the approach. We would highly encourage working with students as partners wherever possible, even when these students are not undertaking specialised education degree streams (Cantrill, 2018).

Adapting your existing experiments

If an existing expository sequence teaches some essential skill and/or illustrates some essential principle, it would be better to adapt rather than scrapping in favour of a new experiment — taking far less time and preserving the robust elements of your established practical. Sequences which run short would be the best candidates for modification initially, followed by experiments that would need elements removed to make space. However, if there is a gap in your curriculum that would require the creation of a new experiment, then incorporating elements of inquiry could be done at the same time.

Student skills development

Your students would start to develop many of the same skills that inquiry, discovery, or problem-based learning laboratories are designed around: motivation, conceptual understanding, higher-order thinking skills, problem-solving ability, experimental design, and other cognitive tasks in laboratory education (Wieman, 2015). Crucially, Szalay and Tóth also found that lower-achieving students were more motivated by student part-designed activities, and this may be particularly valuable to an introductory laboratory. With first year students, affective experiences play a particular role in engagement, attainment, and progression (Szalay and Toth, 2016; Galloway *et al*., 2016).

Assessing your students

When elements of inquiry are used to enhance existing experiments, then existing assessments can serve as a basis for new ones. However, the majority of new assessment should happen outwith the laboratory, split between a pre-laboratory quiz and a post-laboratory report. If you already use pre-laboratory quizzes, these are ideal for assessing preparative calculations. Any new assessment based on an introduced element of inquiry should avoid over-assessing a single task, or assessing a task that does not correlate well with student attainment. For example, if a written procedure is checked by a demonstrator, some features will then be shared by everyone who attends the laboratory. If a mark were to be awarded for a correct procedure, then every student would obtain it, compressing the range of marks available.

Resourcing an implementation

As the approach uses existing expository experiments, there is no need for any new equipment, reagents, teaching time, or timetabled contact hours in the deployment of the approach — only in creation of new written material. Rewriting procedures to include elements of inquiry is a quick process: although this work was the combined output of two undergraduate student projects, the majority of their time was used to evaluate the approach. Modifying expository procedures to include elements of inquiry only took a day or so for each procedure. As most elements of inquiry can be tested at a desk rather than a laboratory, prototyping is rapid. A pilot study with student volunteers would still serve to highlight any issues. This would require additional space or time in a laboratory, along with student volunteers and ethical approval.

Evaluating an implementation

You could evaluate the success of your implementation in a number of ways, some of which we have already presented here:

- A pilot study, to identify any unexpected bottlenecks in the modified procedures or unexpected student anxieties;
- Surveys to measure student perceptions of freedom and control;
- Success of students in subsequent years of laboratory instruction, particularly with non-expository experiments;
- Testing students' ability in experimental design.

Conclusion

Elements of inquiry are short, self-contained modifications to laboratory procedures. They introduce aspects of experimental design and student choice into an expository (recipe-style) sequence. They are quick to introduce, and preserve the robust features of existing experiments. They confer an increased sense of freedom and control, and boost students' experimental design abilities. Students are better prepared for a future practical curriculum that works towards independent research, whether this takes the form of inquiry, PBL, or other innovative laboratory teaching practices. Future work will focus on developing or discovering a greater variety of elements of inquiry, and evaluating their impact on student preparedness for an inquiry learning sequence.

Supplementary Information
Supplementary information referred to in this chapter is available at: overtonfestschrift.wordpress.com.

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