Good Practice Report

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Developing a skills-based practical chemistry programme: an integrated, spiral curriculum approach

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Abstract: Teaching practical laboratory skills is a key component of preparing undergraduate students for future careers in chemistry and elsewhere. In this paper, we present our new strategy to teach practical skills to undergraduate chemistry students. We report a Skills Inventory, a list of the suggested practical skills a graduate chemist should possess; this list was compiled by chemists across the UK. In our new practical course we begin by decoupling the practical skill from the theoretical background, compelling students to first master the basic processes needed to carry out a specific technique. In what we have termed a 'spiral curriculum' approach, skills are revisited on multiple occasions, with increasing complexity and greater emphasis on underlying theory. The new course makes links across traditional subdisciplines of chemistry to avoid compartmentalisation of ideas.

Keywords: integrated; skills inventory; spiral curriculum; undergraduate students.

Introduction

Chemistry laboratory experiments remain at the core of an undergraduate chemistry programme. Professional bodies such as the Royal Society of Chemistry (RSC) and the American Chemical Society (ACS) recognise the importance of laboratory work by placing requirements on accredited courses. For RSC accreditation, students

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are required to complete at least 300 practical hours as part of a bachelor's degree, and at least 400 h, plus a research project, as part of a master's degree (Royal Society of Chemistry, 2022).

As Reid describes very succinctly, the aims of undergraduate laboratory work can be classified under four categories, that is teaching: (i) skills related to learning chemistry, (ii) practical skills, (iii) scientific skills and (iv) transferable skills (Carnduff & Reid, 2003; Reid & Shah, 2007). During a chemistry degree, students are expected to master a variety of laboratory techniques and skills. A comprehensive inventory of the skills expected of a chemistry graduate has not been reported to date. Such a list could enable institutions to identify areas of strength and weakness within their current course and design a practical course which reinforces the learning of these skills.

It has often been stated that the aims of a practical course should be to reinforce students' theoretical learning, by providing real world examples of the theory they have studied (Blosser, 1980; Bryce & Robertson, 1985; Hofstein, 2004; Hofstein & Lunetta, 1982, 2003; Lazarowitz & Tamir, 1994). This approach of linking theory and practice, however, appears to have little impact on developing students' understanding of concepts in chemistry (Reid & Shah, 2007). In fact, the significant cognitive load demand placed on students in an unfamiliar laboratory setting reduces the ability of students to think clearly about the theory underpinning the task at hand (Hennah & Seery, 2017). An undergraduate practical chemistry programme should therefore establish a foundation of practical skills, rather than fitting laboratory experiments around theory learnt in lectures (Seery, 2020).

There are a number of barriers to student learning in the laboratory. Students can find it challenging to apply knowledge gained in one branch of chemistry, to situations in another branch (Domin, 1999). This is particularly noticeable when laboratory work is taught along traditional boundaries of inorganic, organic, physical and analytical chemistry. We have ourselves observed these challenges in the lab; students can struggle to rationalise organic reaction pathways using thermodynamic concepts. The issues can also manifest in practical techniques. We have observed students conducting inorganic practicals attempting to remove flammable solvents on hotplates, illustrating that students had compartmentalised the use of rotary evaporators as an organic technique.

When designing chemistry laboratory practicals to fit within the traditional discipline boundaries, students may miss the opportunity to make connections between different areas of chemistry. The approach also poorly prepares students for careers in research, where boundaries between subject disciplines are more loosely defined and working across multiple disciplines is increasingly common.

Rethinking how chemistry practicals are designed, with a focus of preparing students for research, allows us to move away from traditional 'cookbook' style practicals. By introducing aspects of experimental design into the undergraduate practical course, students are able to develop the problem-solving skills required of a scientist. Introduction of experimental design into chemistry practical programmes is becoming increasingly commonplace (Carnduff & Reid, 2003; Reid & Shah, 2007). We have also reported such work recently, particularly aimed at the early stage of an undergraduate practical course (Smallwood, Campbell, Worrall, Cahill, & Stewart, 2021).

Undergraduate practical chemistry at Oxford

In common with other UK universities, at the University of Oxford assessment of practical chemistry sits alongside written examinations and a final year research project in contributing to the final degree classification awarded.

We had the opportunity to redesign our practical chemistry course, to coincide with the completion of a new teaching laboratory facility in 2018. Previously, the course was taught separately by three different teams, split along IOP (inorganic, organic, physical) boundaries. In our redesigned course, these teams were unified to create one Chemistry Teaching Laboratory. The new team have complete oversight over practical chemistry course design and delivery in the first three years of the four-year MChem programme. The course redesign gave us the opportunity to rethink how we teach our undergraduate chemistry students practical chemistry. We were able to reassess the skills and qualities we believed a chemistry graduate should possess, and align our teaching accordingly.

A clear set of objectives for the new course was established and laid out in the course Mission Statement:

The overarching aim of the undergraduate practical course is to inspire an awareness, appreciation and enjoyment of practical science. We aim to achieve this by focusing on a number of more specific, tangible aims:
1. To promote safe laboratory working practices;
2. To develop practical and problem-solving skills;
3. To provide an experimental foundation for theoretical concepts and phenomena;
4. To introduce students to scientific practices as used by the scientific community;
5. To promote aspects of scientific thinking;
6. To improve communication skills, including proficiency at scientific writing.

This report details the processes and considerations made in the construction of our new integrated practical chemistry course, placing skills development at its core. In this report, we will focus on the redevelopment of the first-year course. Future publications will follow detailing the second- and third-year course.

Course design considerations

We began the practical chemistry course redesign by compiling a list of skills that chemistry graduates should possess. It was essential to structure the practical course so that these skills could be taught effectively. In considering this, two strategies were identified. The first is that practical skills should be taught as an integrated course, bridging the chemistry subdisciplines. Secondly, we identified that teaching complex practical skills requires the skills to be broken down into smaller, more manageable pieces. We have designed the course so that initially teaching the skill and the underlying theory is decoupled. Once students are more confident with a subject, the skill is revisited with increasing levels of complexity. We have referred to this approach as teaching in 'skills spirals'.

A skills-based practical course

In collaboration with chemists from 37 UK higher education institutions, and the RSC, compilation of a Skills Inventory was conducted. The list originated from the 'Future of Labs' conference at Oxford in 2015. We led a discussion session, presenting a skills list our team had devised. Participants edited this list anonymously during the session (via Mentimeter) and it was then circulated after the session for participants to make any further comments. The inventory was edited based on the feedback, presented and further refined at national conferences in Oxford in 2017 ('What makes a Good Lab?') and 2020 ('Skills in Chemistry and Physics').

The skills were classified into 12 separate categories. Within each of the various categories, skills were designated a level, based on expectations of students' prior experience, theoretical understanding required, technical difficulty and safety considerations. These levels were defined:
(a) Basic skills: essential skills needed from year one of the practical course;
(b) Intermediate skills: skills that were more theoretically and/or technically more advanced than those in the Basic category;
(c) Advanced/Optional: more demanding or specialised skills that built upon and extended those covered in the Intermediate category, aimed towards research level application.

Table 1 shows the full Skills Inventory. Skills categorised as 'Basic' are fundamental introductory skills. They are both technically and theoretically accessible at early stages of the student's degree. These skills provide a foundation and are a gateway to both more advanced and widely used techniques. The more demanding skills form the 'Intermediate' skills, which should be completed by students by the end of the practical course.

Skills within the 'Advanced/Optional' category require significantly greater technical and theoretical considerations. They may use particular specialised instrumentation or involve more complex operational considerations. These 'Advanced/Optional' skills provide students with opportunities to explore particular areas of interest, prior to completion of research in the final year research project. Teaching these skills are opportunities for institutions to showcase their own expertise and specialities.

Table 1: Skills Inventory compiled in collaboration with academics from 37 UK higher education institutions across the UK. The skills are sorted into Skill Groups and are categorised as Basic, Intermediate (Int.) or Advanced/Optional (Adv.).

Skill Group	Specific Skill	Basic	Int.	Adv.
General scientific skills	Make careful and accurate observations	✓		
	Make a proper record of observations	✓		
	Draw appropriate graphs neatly and efficiently	✓		
	Exhibit best practice with regard to ethical scientific behaviour	✓		
	Keep accurate scientific notes	✓	✓	
	Prepare a report, describing the reasoning for conclusions	✓	✓	
	Develop the ability to design experiments	✓	✓	
	Be able to work well alone and as part of a team	✓	✓	
Laboratory safety	Awareness of emergency procedures	✓		
	Proper storage of chemicals	✓		
	Proper disposal of chemicals (including organic solvents)	✓		
	Identification of known toxic substances and other hazards	✓		
	Proper disposal of sharps and broken glass	✓		
	Choice of suitable heating and cooling methods	✓		
	Choice of suitable concentrations	✓		
	Safe handling of syringes and needles	✓	✓	
	Safe use of vacuum lines and gas cylinders	✓	✓	
	Safe handling of cryogenic liquids and solids		✓	
General technique	Correct use and care of balances	✓		
	Proper use of volumetric glassware, reading a meniscus	✓		
	Use of appropriate thermometers for a given measurement	✓		
Liquid handling	Choice of appropriate glassware, including required precision	✓		
	Use of pipettes	✓		
	Use of burettes	✓		
	Preparation of molar, volume percent, and mass/volume solutions	✓		
	Proper dilution of solutions	✓		
	Methods for solution filtration	✓		
	Choice of suitable concentrations	✓		
	Appropriate methods of carrying, pouring and shaking liquids, including ultrasound/sonication	✓	✓	
Handling of gases	Pressure measurements	✓		
	Use of vacuum lines	✓	✓	
	Safe use of gas cylinders and pressure regulators		✓	
	Use and maintenance of vacuum pumps		✓	
Preparative/synthetic methods	Use of hotplates and other heating methods	✓		
	Use of reflux apparatus	✓		
	Multi-step syntheses	✓		
	Synthetic electrochemistry	✓	✓	✓
	Solid state techniques		✓	
	Inert atmosphere methods		✓	
	Schlenk line techniques		✓	✓
	Microscale techniques		✓	
	High-pressure methods			✓
	Glove box techniques			✓
	Nanoparticle and thin film synthesis			✓
Purification and separation techniques	Distillation	✓		
	Recrystallisation	✓		
	Solvent extraction	✓		
	Vacuum filtration	✓		
	Thin layer chromatography	✓		
	Column chromatography	✓	✓	
	Sublimation		✓	
	Gel electrophoresis		✓	

Table 1: (continued)

Skill Group	Specific Skill	Basic	Int.	Adv.
Thermodynamic and kinetics measurements	Enzyme assays and kinetics measurements	✓		
	Bomb calorimetry	✓		
	Solution calorimetry	✓		
	Thermal analysis (differential scanning calorimetry)		✓	
	Cyclic voltammetry		✓	
	Stopped flow kinetics measurements		✓	✓
	Photometric kinetics measurements and flash photolysis			✓
General analytical techniques	Use of melting point apparatus	✓		
	Use of analytical balances	✓		
	Titrations (acid-base, complexometric, redox, precipitate)	✓		
	Qualitative techniques for inorganic analysis	✓		
	Gravimetric analysis	✓		
	Use of pH paper and pH meters, including calibration	✓		
	Use of magnetic balance	✓		
	Electrochemical technique, including preparation of electrodes	✓		
	Gas chromatography/mass spectrometry		✓	
	High performance liquid chromatography		✓	
	Powder X-ray diffraction	✓	✓	
	Conductivity measurements		✓	
Spectroscopic, spectrometric, and optical techniques	Infrared spectroscopy	✓		
	UV/vis spectroscopy	✓		
	Polarimetry	✓		
	NMR spectroscopy (including multinuclear and solid state)	✓	✓	✓
	Mass spectrometry	✓	✓	
	Raman spectroscopy		✓	
	Fluorimetry		✓	
	ESR spectroscopy		✓	
	Optical microscopy		✓	
	Use and care of optics		✓	
	Atomic spectroscopy		✓	
	Atomic force microscopy			✓
Data analysis	Distinguish between accuracy and precision	✓		
	Calculate and report measurement uncertainties	✓		
	Use significant figures properly	✓		
	Use units properly	✓		
	Use correct chemical formulae and correctly balanced equations	✓		
	Apply appropriate statistical analysis	✓	✓	
	Graph plotting and curve fitting	✓		
	Be able to identify point groups		✓	
	Be able to use crystal structure parameters		✓	
	Analysis of ^{1}H and ^{13}C NMR data	✓	✓	
	Analysis of IR and UV/vis spectra	✓		
	Analysis of powder X-ray diffraction data (search/match and Rietveld methods)		✓	✓
IT skills	Use of word processing and spreadsheet packages (e.g. Microsoft Word, Excel)	✓		
	Use of software packages (e.g. ChemDraw, Origin, LabVIEW)	✓	✓	
	Computational chemistry and chemical simulations	✓	✓	
	Basic coding skills	✓		
	Search/use of Internet resources	✓		
	Chemometrics		✓	
	Literature searches, including Web of Science, SciFinder, Reaxys		✓	
	Use of electronic laboratory notebooks		✓	
	Preparation of journal articles		✓	

It should be emphasised that the Skills Inventory was compiled as a means of identifying skills that could be used to form a course, but not as a prescriptive list to be covered by the course. Indeed, we have ourselves distilled this list to fit our facilities and the expertise within our institution. The list covers only the laboratory and laboratory related skills. Laboratory work also fosters numerous transferable skills such as: communication (e.g. oral, scientific writing), team working, organization and time management. Coverage of these transferable skills should be woven into the structure of the whole degree.

Pedagogical considerations

With our established Skills Inventory, we next addressed how teaching these skills could be achieved. Our approach was to develop a practical programme that recognises students' prior experience and then progressively builds upon this. Our aim is to provide both breadth of exposure to a range of experimental techniques and sufficient repeated experience of these skills to facilitate knowledge retention. The structure of the new course enables students to build a skills portfolio (Wright, Read, Hughes, & Hyde, 2018); parallels here can be drawn with similar initiatives, including the introduction of core skills to the UK A-Level chemistry curriculum, known as the practical endorsement (C. Smith, 2018), the digital badging concept (Hennah & Seery, 2017), and the recent reconstruction of UK introductory chemistry courses (Adams, 2020; Gorman, Holmes, Brooke, Pask, & Mistry, 2021). Our approach expands upon such remits, considering the development of skills across the full undergraduate chemistry practical programme.

Crucially, we set out to impart understanding of why particular techniques/skills were chosen to perform certain tasks, alongside how those techniques are performed. By placing an emphasis on both the "how" and "why", students hopefully gain a greater appreciation of the practical work they are conducting. This explanation-driven approach has been extensively demonstrated to be more effective than fact driven methods (Bransford, Brown, & Cocking, 2000; Coleman, 1998; Hakkarainen, 2004; Lipponen, 2000). Our vision is to create a course where students are developed into problem-solvers, not recipe followers.

An integrated practical course

A key aspect of developing our new course was considering the best means to reflect the truly integrative nature of chemistry, not as a science segregated into silos. To fulfil our aim for a progressive development programme, we set out our course as a series of specifically developed practicals, rather than separating the practical course by subdiscipline. The design allows for chemistry to be presented as a connected science and in this way, there are opportunities for enrichment of the student experience through multidisciplinary teaching. Similar strategies have been highlighted by Hardy et al.; in their recent publication they discuss the advantages of multidisciplinary teaching in improving affective and cognitive learning and critical thinking (Hardy et al., 2021). We aim to develop a systems-thinking approach in our students, allowing them to think about chemistry more deeply and in a less compartmentalised manner (Mahaffy, Krief, Hopf, Mehta, & Matlin, 2018; Nagarajan & Overton, 2019).

It was important to recognise that each individual practical session does not need to deliver a multi-faceted experience of chemistry; certain skills are sufficiently complex and important to one branch of chemistry that they require individual focus. When possible, we highlight common threads for skills and techniques which are relevant across sub-disciplines. We have been careful to design practicals so that we do not introduce multiple new skills to students in one practical session, with the aim of eliminating cognitive overload.

Repeat exposure and a spiral curriculum

A major challenge for any practical course is ensuring skills retention. Students must be able to recall and execute practical tasks they have had previous experience in performing. In this regard, both confidence and competence are important considerations (Hensiek et al., 2016; Pullen, Thickett, & Bissember, 2018).

We chose to adopt a repeat exposure strategy as a means to solidify key practical skills learnt by our students (Anderson, 1999; Brown & Bennett, 2002). We have aimed to strike a careful balance between repetition to develop confidence, and the potential for repetition to lead to reduced student engagement (Acee et al., 2010; Galloway & Bretz, 2016; Supalo, Humphrey, Mallouk, David Wohlers, & Carlsen, 2016; Trehan, Brar, Arora, & Kad, 1997). As noted by Campitelli and Gobet:

> "Rote repetition — simply repeating a task — will not by itself improve performance." (Campitelli & Gobet, 2011)

> "Deliberate practice consists of activities purposely designed to improve performance." (Campitelli & Gobet, 2011)

It was therefore important that we developed a course where there are sufficient differences each time a skill is revisited. To achieve this, we applied the use of a spiral curriculum. The defining features of this pedagogical approach are outlined below (Harden & Stamper, 1999):
- Reinforcement—encourages retention of knowledge;
- Simple to complex—topics can be introduced in a manner to build up complexity, to enable better understanding;
- Integration—enables connectivity with different aspects of the course to be linked readily;
- Logical sequence—a logical thread to lead through the various topics can be created at the curriculum design stage;
- Higher level objectives—the model encourages students to move beyond knowledge recall, to application of knowledge and skills.

The use of spiral curricula has some precedence in secondary education (Bruner, 1977; Schmidkunz & Büttner, 1986) and tertiary chemical education, particularly organic chemistry (Gravert, 2006; Grove, Hershberger, & Bretz, 2008; Minter & Reinecke, 1985; Sartoris, 1992), but is still relatively unexplored in higher education chemistry teaching.

We envisaged a new strategy to teach students requisite practical skills. Early practicals would concentrate on the essence of any new technique. The skill would then be revisited at various later stages, covering more technical aspects and applications of the skill and gradually introducing new chemical theory. The process allows theory and practical skills to be decoupled and provides a mechanism for students to focus on learning the technique at the earlier stages. We believe the strategy provides students with greater opportunities to develop a stronger understanding of each individual skill, whilst also allowing students to create links between concepts when they are revisited.

An important aspect of our redesign was to consider the regularity in which students revisit skills. To emphasise the importance of key skills, students revisit these frequently, both within each year of the practical course and year-on-year as students progress. Throughout their degree, their knowledge and application of the skills is built upon and expanded. When a significant period of time has elapsed since students last practised a skill, we first take a step back to ensure their foundation knowledge is strong; we think of this as 'winding back the spiral'. The foundation is then built upon and new practical skills or theory are introduced.

Practicals have been designed so that when a skill is encountered frequently, it sits alongside students learning new skills and techniques; in this way it is hoped we can reduce student ennui. By combining the spiral curricular design with an integrated practical chemistry programme, skills can be showcased in multiple scenarios across the disciplines. This approach enables students to develop greater familiarity and confidence in performing practical chemistry in a variety of scenarios, thereby improving students' effectiveness as future researchers.

Course structure

Having set out the larger objectives of the new course and how skills spirals would be introduced, we next turned to addressing the overall course design.

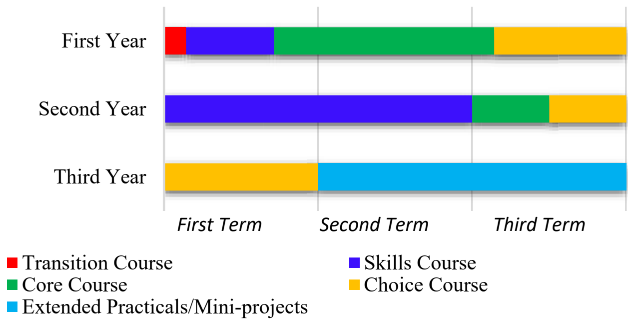

Figure 1: Structure of the three-year practical course.

The course was designed with the following structure (as shown in Figure 1):

- Pre-university skills revision (referred to as the Transition Course) – for first-year students only
- Skills introduction (referred to as the Skills Course)
- Skills reinforcement (referred to as the Core Course)
- Skills utility, and application to more advanced scenarios (referred to as the Choice Course)
- Extended practicals and mini-projects – for third-year students only

The spiral nature of the complete practical course is displayed graphically in Figure 2. To date, we have taught our first-year course and this will be discussed in detail in this paper. We have also taught our new second-year course; however, evaluation of this course was disrupted during the COVID-19 pandemic. Likewise, the pandemic has disrupted our plans to teach the third-year course and so only the plan for this course is outlined below.

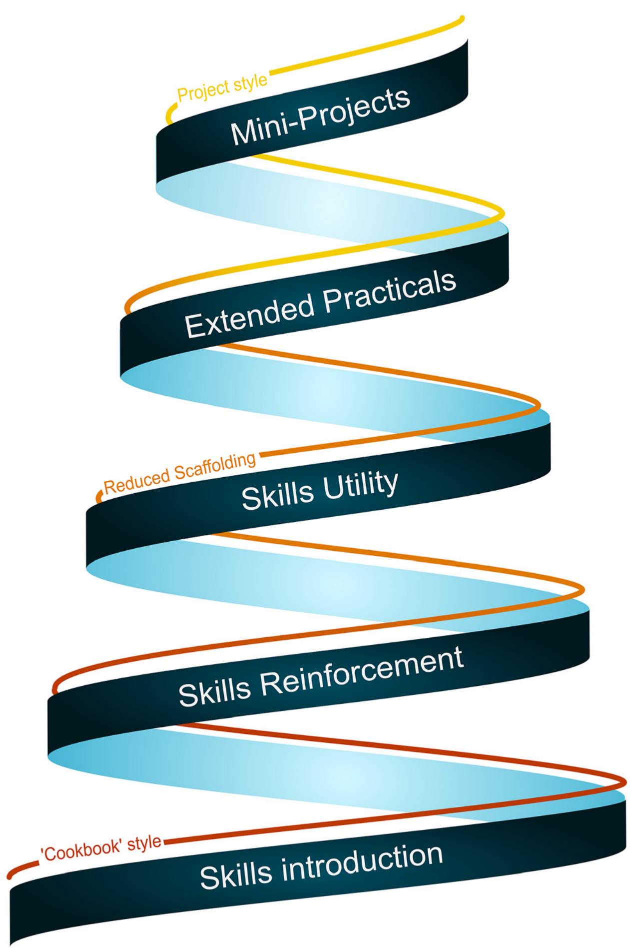

Figure 2: Structure of our new practical course based on a spiral curriculum students start at the bottom of the spiral, in cookbook-style introductory labs. Throughout the three-year course, they progress up the spiral, ultimately carrying out research-style mini-projects in their third-year.

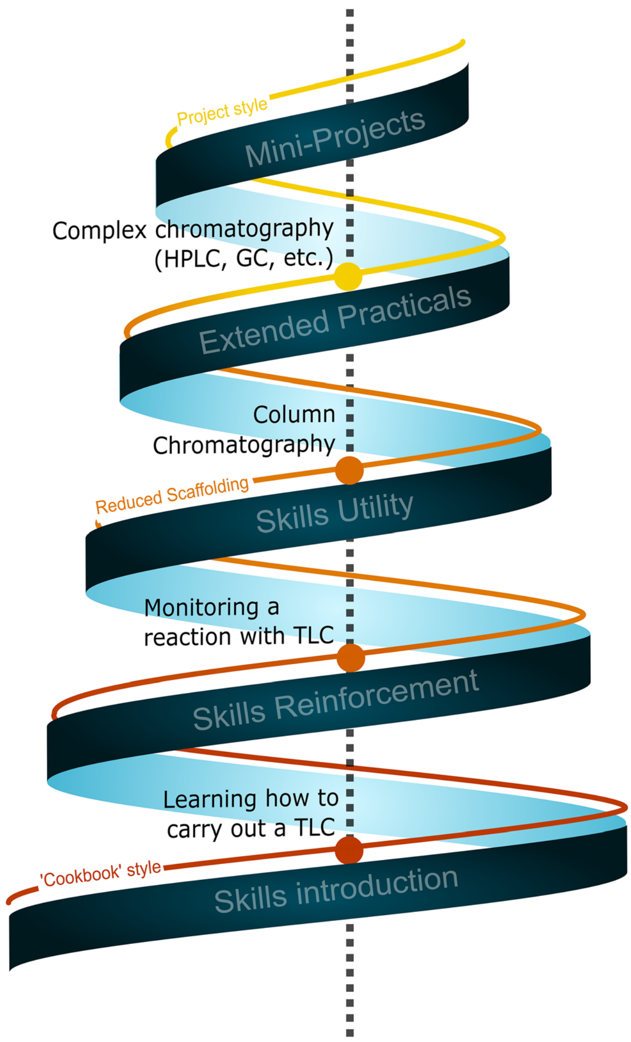

Figure 3: Skill spiral of chromatography starting at the bottom with the introduction to the skill and learning how to carry out a TLC and moving ultimately to mastery of specialist techniques, such as HPLC and GC.

The Transition Course: supporting the transition between school and higher education

As part of our new practical course we developed a 'Transition Course'. This was created in response to reports published by Gagan (Gagan, 2008) and Smith (C. J. Smith, 2012), suggesting that in recent years there has been a decline in the practical skills and problem-solving skills of students entering university. We recognise the differences in educational experiences of our new first-year students and our Transition Course aims to provide a foundation, smoothing over some of the inconsistencies in the students' pre-university education (Turner, 2019). Several members of our team have extensive experience in teaching chemistry at A-Level and we were able to draw upon their experience in constructing our Transition Course. The course serves to build students' confidence in the new laboratory setting and provides a grounding for all subsequent practical work.

In choosing content for the Transition Course, we used a range of resources. A review of the practical skills of A-level science students in England was carried out by The Office of Qualifications and Examinations Regulation (Ofqual), in collaboration with a number of UK universities, including our own institution (Cadwallader, 2018). Universities conducted assessments of the practical competencies of their new cohorts across five selected tasks from the A-Level Practical Endorsement. Each institutions' educators evaluated their new cohort's practical skills in performing key skills covered during the A-Level programme. Student performance was assessed against a set of prescribed criteria for each of the tasks.

Table 2: Extracted data from Ofqual report examining competency with selected A-Level chemistry skills from the Practical Endorsement (2017 cohort) (Cadwallader, 2018).

Task	Description	% Criteria Met
1	Setting up a burette	64
2	Thin layer chromatography	59
3	Setting up a reflux and distillation	70
4	Making up a standard solution	82
5	Iodine clock (kinetics)	62

Table 3: Structure of the Transition Course. Students complete these introductory experiments as the first four practicals on the three-year practical course.

Experiment no.	Key Skills
1	Biphasic extraction, rotary evaporation
2	Recrystallisation, vacuum filtration
3	IR, NMR, UV/vis spectroscopy
4	Thin layer chromatography

A selection of the data from the compiled report is shown in Table 2. The results from the review helped identify the skills and techniques which would most benefit from being included in our Transition Course.

It is also necessary to introduce some new skills to all the students, at the very beginning of their practical chemistry education. Risk Assessment and Control of Substances Hazardous to Health (COSHH) were deemed essential considerations prior to conducting all practical work, thus it is necessary to introduce this at the very beginning as a new skill. Instruments used routinely for synthetic work are introduced (e.g. IR and NMR spectrometers), so students can gain familiarity with these from the outset. Students study spectroscopy pre-university and our Transition Course builds on this knowledge by teaching students how to use the relevant spectrometers, as well as spectral interpretation.

The key skills in our Transition Course are shown in Table 3. Most of the concepts and tasks were chosen to be familiar to students, thereby reducing the introduction of many new skills at the outset.

The Skills Courses

The Skills Courses are considered a major focus of students' development in the first two years of the practical course. The emphasis is developing students' confidence and competency with practical techniques. There are four fundamental aims:

(a) to reinforce and revisit techniques with which students would be familiar from their previous experience;
(b) to expand the underlying theoretical understanding of the familiar techniques;
(c) to illustrate practical applications of techniques and skills;
(d) to introduce new techniques that could be utilised throughout their future scientific career.

In the practicals within the Skills Courses, the focus of any particular experiment is to gain familiarity with a new skill or build complexity into a previously encountered skill or technique. The practicals in the Skills Courses were constructed to utilise a small selection of the individual skills in one practical session. For those that were considered more technically demanding or relatively important, we have designed multiple experiments where that particular skill is practised, in a variety of different contexts.

The Core Courses

Practicals in the Core Courses were designed to reinforce skills learnt in the Skills Course. These particular skills are clearly referenced in the laboratory manuals to remind students of their previous experience and students are signposted to the practicals where they previously used these skills. Practicals in the Core Courses are more intellectually challenging; skills and techniques that were learnt previously in the Skills Courses are applied to more complex scientific problems. In experiments in the Core Course, often a broad range of skills are practised in one practical. When skills have been practised repeatedly, gradual de-scaffolding of the laboratory protocol is implemented. This strategy aims to build student confidence and ability to problem solve, and maximise engagement.

The Choice Courses

At the end of the first-year, students have some choice as to the practicals they would like to carry out. This gives them opportunities to investigate areas of chemistry in which they have a particular interest. These experiments are not pre-requisites for any practicals in following years so students do not limit their options by choosing one choice practical over another.

By the end of the second year of the practical course and into the third-year, students will be provided with opportunities to develop some specialisation in areas that interest them most. The labs offered will involve applications of the skills introduced previously or they will introduce new skills. These new skills (shown as advanced in the Skills Inventory) will be related to the use of more specialist equipment. The approach forges important collaborations with research groups within the department and provides students with greater appreciation of the research laboratory environment.

The extended projects aim to provide a stepping stone into students' final year research projects and will emphasise the integrated nature of chemistry research. The projects will promote student autonomy, allowing students to take responsibility for their own learning (Burnham, 2019). Development of open-ended third-year mini-projects is an evolving aspect of our new undergraduate practical chemistry course and we expect to publish further about these in the future.

Construction of individual labs

We were influenced by educational literature when structuring our labs; each practical was constructed within the established structure of pre-lab, in-lab and post-lab (Agustian & Seery, 2017; Carnduff & Reid, 2003; Reid & Shah, 2007).

Identification of learning objectives

The first step in developing each new practical was identifying the learning objectives; these objectives were kept at the forefront of all practical development work. Using the Skills Inventory, we mapped how skills were developed across each year and across the full practical course.

The learning objectives for each practical are explicitly stated as this allows students to recognise the core skills they are developing when conducting each practical. As students progress throughout each year, significantly more investigative practicals are introduced. This ensures students have opportunities to develop and implement experimental design, formulate hypotheses and interpret their own data. A number of practicals were developed so that students were not able to predict the outcome, even as early as the first-year course. An example of this is the combinatorial discovery of new potential antibiotics based on the guanofuracin framework (Wolkenberg & Su, 2001). In this practical, students devise their own experimental conditions and evaluate the properties of the resulting products.

Pre-lab preparation

As established in the literature, pre-lab exercises are used to guide student preparation before they enter the laboratory. These include pre-lab quizzes (Spagnoli, Rummey, Man, Wills, & Clemons, 2019), videos (Jolley, Wilson, Kelso, O'Brien, & Mason, 2016), and computer simulations (Blackburn, Villa-Marcos, & Williams, 2019). The pre-lab exercises are accessed via our virtual learning environment and are available to students as they progress through the course.

In a departure from previous literature, pre-lab exercises are designed to focus on the practical technique, rather than the underlying theory. Our videos are filmed in house, tailored to our course design and feature the staff and exact laboratory equipment students will be encountering. The pre-lab exercises aim to reduce student cognitive load during the practical by enabling the students to familiarise themselves with techniques before they enter the laboratory.

In-lab

An essential part of learning in the laboratory is communication between undergraduate students and both PhD student demonstrators and teaching staff (Flaherty, Overton, O'Dwyer, Mannix-McNamarra, & Leahy, 2019). We include in-lab questions in the laboratory manual to promote discussion during practical sessions. The questions aim to encourage students to consider the purpose of the steps whenever particular operations are performed.

The laboratory manuals for practicals utilise a mixture of instructional styles throughout the new first-year practical course (Domin, 1999). Practicals that focus on introducing skills are predominantly expository in nature, with explicit procedural instructions given. As students progress through the Skills Course and into the Core Course, scaffolding is gradually reduced.

Post-lab write up

All laboratories are assessed by each student producing a post-lab write up, the requirements for these depend upon the laboratory course. In the Transition Course, post-lab write ups are constructed as worksheets. The students are led through the process of writing up their results and are expected to answer questions about the practical and their experimental data.

In the Skills Courses and Core Courses, scaffolding is removed and students are expected to construct their own post-lab write up. Some guidance is provided in the laboratory manual in the form of post-lab questions; students are expected to provide answers to these in their write up. The write up must then be discussed in person with a member of the teaching team. Here, student's knowledge and understanding can be explored face-to-face.

Case study

Skills-based spiral curriculum: chromatography

The subject of chromatography serves as a suitable example of how we constructed skills spirals in the new practical chemistry course. The theory and applications of chromatography are varied and have uses across all disciplines in chemistry. Thus, a 'spiral' of chromatography in its various forms was constructed (Figure 3).

Thin layer chromatography (TLC) is a technique encountered pre-university and students are re-introduced to TLC as an identification technique in the Transition Course. Here, they are also taught the practical technique needed to carry out TLC. In later practicals in the Skills and Core Courses, uses of TLC in synthetic chemistry are introduced, for example its use in reaction monitoring. Moving further up the skills spiral, column chromatography is taught to our first-year students in the Skills Course. Students are taught the fundamentals of silica gel column chromatography in a practical where a mixture of fluorene and fluorenone is separated. In the second year, students extract caffeine from tea bags and purify the product by silica gel column chromatography. In this practical the students are expected to optimise the column conditions.

Finally, more advanced separation techniques are introduced. In the second- and third-year Choice Courses, the concept is expanded to quantification of mixtures by gas chromatography (GC), separation of enantiomers by chiral high performance liquid chromatography (HPLC) and macromolecular separation by size exclusion chromatography.

To achieve such a progression, students are required to gain sufficient theoretical understanding of the scientific processes underpinning chromatography, as well as mastering the practical techniques needed to perform these processes.

Conclusions and outlook

The construction of a new skills-based practical course has been completed and implemented for first-year students at the University of Oxford. The course has been developed using a newly created inventory of the skills and techniques fundamental to practical chemistry. The compiled Skills Inventory provides a framework, shaping the construction of our practical chemistry programme. We place developing skills at the core of our new practical course, with two approaches to our teaching strategy. One is a spiral curriculum, where skills are revisited throughout the degree, building first competency and then expertise. The second is that the programme does not segregate practicals along subdiscipline boundaries and instead skills are taught in a variety of contexts.

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References

Acee, T. W., Kim, H., Kim, H. J., Kim, J. I., Chu, H. N. R., Kim, M., & Wicker, F. W. (2010). Academic boredom in under- and over-challenging situations. *Contemporary Educational Psychology*, *35*(1), 17–27.

Adams, C. J. (2020). A constructively aligned first-year laboratory course. *Journal of Chemical Education*, *97*(7), 1863–1873.

Agustian, H. Y., & Seery, M. K. (2017). Reasserting the role of pre-laboratory activities in chemistry education: A proposed framework for their design. *Chemistry Education Research and Practice*, *18*(4), 518–532.

Anderson, J. R. (1999). *Learning and memory: An integrated approach* (2nd ed.). New York: John Wiley & Sons.

Blackburn, R. A. R., Villa-Marcos, B., & Williams, D. P. (2019). Preparing students for practical sessions using laboratory simulation software. *Journal of Chemical Education*, *96*(1), 153–158.

Blosser, P. E. (1980). *A Critical Review of the Role of Laboratory in Science Teaching*. Columbus, OH: Information Reference Centre, The Ohio State University. http://www.eric.ed.gov/ERICWebPortal/detail?accno=ED206445.

Bransford, J., Brown, A. L., & Cocking, R. R. (Eds.) (2000). *How people learn: Brain, mind, experience, and school (Expanded e)*. Washington, DC: National Academies Press.

Brown, S. W., & Bennett, E. D. (2002). The role of practice and automaticity in temporal and nontemporal dual-task performance. *Psychological Research*, *66*(1), 80–89.

Bruner, J. (1977). *The Process of Education* (1st ed.). New York: Harvard University Press.

Bryce, T. G. K., & Robertson, I. J. (1985). What can they do? A review of practical assessment in science. *Studies in Science Education*, *12*(1), 1–24.
Burnham, J. A. J. (2019). Developing student expertise in scientific inquiry. In Seery, M. K., & McDonnell, C. (Eds.), *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton* (1st ed., pp. 391–404). Dublin: Creathach Press.
Cadwallader, S. (2018). *The impact of qualification reform on the practical skills of A level science students Paper 2: Pre- and post-reform evaluation of science practical skills (Ofqual report)*. Ofqual. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/792663/A_level_science_paper_2.pdf.
Campitelli, G., & Gobet, F. (2011). Deliberate practice: Necessary but not sufficient. *Current Directions in Psychological Science*, *20*(5), 280–285.
Carnduff, J., & Reid, N. (2003). In J. Johnston (Ed), *Enhancing undergraduate chemistry laboratories: Pre-laboratory and post-laboratory exercises* (1st ed.). London: Royal Society of Chemistry.
Coleman, E. B. (1998). Using explanatory knowledge during collaborative problem solving in science. *Journal of the Learning Sciences*, *7*(3–4), 387–427.
Domin, D. S. (1999). A review of laboratory instruction styles. *Journal of Chemical Education*, *76*(2–4), 543–547.
Flaherty, A., Overton, T. L., O’Dwyer, A., Mannix-McNamarra, P., & Leahy, J. J. (2019). Working with graduate teaching assistants to enhance chemistry laboratory teaching. In Seery, M. K., & McDonnell, C. (Eds.), *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton* (1st ed., pp. 421–434). Dublin: Creathach Press.
Gagan, M. (2008). *Review of the student learning experience in chemistry*. The Higher Education Academy. https://www.advance-he.ac.uk/knowledge-hub/review-student-learning-experience-chemistry.
Galloway, K. R., & Bretz, S. L. (2016). Video episodes and action cameras in the undergraduate chemistry laboratory: Eliciting student perceptions of meaningful learning. *Chemistry Education Research and Practice*, *17*(1), 139–155.
Gorman, S. A., Holmes, K., Brooke, G., Pask, C. M., & Mistry, N. (2021). Repurposing an introductory organic and inorganic laboratory course from the focus on teaching theory to the focus on teaching practical technique. *Journal of Chemical Education*, *98*(6), 1910–1918.
Gravert, D. J. (2006). Two-cycle organic chemistry and the student-designed research lab. *Journal of Chemical Education*, *83*(6), 898–901.
Grove, N. P., Hershberger, J. W., & Bretz, S. L. (2008). Impact of a spiral organic curriculum on student attrition and learning. *Chemistry Education Research and Practice*, *9*(2), 157–162.
Hakkarainen, K. (2004). Pursuit of explanation within a computer-supported classroom. *International Journal of Science Education*, *26*(8), 979–996.
Harden, R. M., & Stamper, N. (1999). What is a spiral curriculum? *Medical Teacher*, *21*(2), 141–143.
Hardy, J. G., Sdepanian, S., Stowell, A. F., Aljohani, A. D., Allen, M. J., Anwar, A., & Wright, K. L. (2021). Potential for chemistry in multidisciplinary, interdisciplinary, and transdisciplinary teaching activities in higher education. *Journal of Chemical Education*, *98*(4), 1124–1145.
Hennah, N., & Seery, M. K. (2017). Using digital badges for developing high school chemistry laboratory skills. *Journal of Chemical Education*, *94*(7), 844–848.
Hensiek, S., Dekorver, B. K., Harwood, C. J., Fish, J., O’Shea, K., & Towns, M. (2016). Improving and assessing student hands-on laboratory skills through digital badging. *Journal of Chemical Education*, *93*(11), 1847–1854.
Hofstein, A. (2004). The laboratory in chemistry education: Thirty years of experience with developments, implementation and research. *Chemistry Education, Research and Practice*, *5*(3), 247–264.
Hofstein, A., & Lunetta, V. N. (1982). The role of the laboratory in science teaching: Neglected aspects of research. *Review of Educational Research*, *52*(2), 201–217.
Hofstein, A., & Lunetta, V. N. (2003). The laboratory in science education: Foundations for the twenty-first century. *Science Education*, *88*(1). 28–54 http://onlinelibrary.wiley.com.ezproxy1.lib.asu.edu/doi/10.1002/sce.10106/abstract.
Jolley, D. F., Wilson, S. R., Kelso, C., O’Brien, G., & Mason, C. E. (2016). Analytical thinking, analytical action: Using prelab video demonstrations and e-quizzes to improve undergraduate preparedness for analytical chemistry practical classes. *Journal of Chemical Education*, *93*(11), 1855–1862.
Lazarowitz, R., & Tamir, P. (1994). Research on using laboratory instruction in science. In S. K. Abell, & N. G. Lederman (Eds.), *Handbook of research on science teaching and learning* (1st ed.). New York: Routledge.
Lipponen, L. (2000). Towards knowledge building: From facts to explanations in primary students’ computer mediated discourse. *Learning Environments Research*, *3*(2), 179–199.
Mahaffy, P. G., Krief, A., Hopf, H., Mehta, G., & Matlin, S. A. (2018). Reorienting chemistry education through systems thinking. *Nature Reviews Chemistry*, *2*(4), 1–3.
Minter, D. E., & Reinecke, M. G. (1985). Two-cycle organic chemistry: An alternative to course proliferation. *Journal of Chemical Education*, *62*(1), 77–79.
Nagarajan, S., & Overton, T. (2019). Promoting systems thinking using project- and problem-based learning. *Journal of Chemical Education*, *96*, 2901–2909.

Pullen, R., Thickett, S. C., & Bissember, A. C. (2018). Investigating the viability of a competency-based, qualitative laboratory assessment model in first-year undergraduate chemistry. *Chemistry Education Research and Practice*, *19*(2), 629–637.

Reid, N., & Shah, I. (2007). The role of laboratory work in university chemistry. *Chemistry Education Research and Practice*, *8*(2), 172–185.

Royal Society of Chemistry. (2022). *Accreditation of degree programmes*. London, UK: Royal Society of Chemistry. http://www.rsc.org/images/Accreditation criteria 2017-updatejuly 17_tcm18-151306.pdf.

Sartoris, N. E. (1992). Two-cycle organic chemistry: A sound pedagogic alternative to the traditional year-long course. *Journal of Chemical Education*, *69*(9), 750–752.

Schmidkunz, H., & Büttner, D. (1986). Teaching chemistry according to a spiral curriculum. *European Journal of Science Education*, *8*(1), 9–16.

Seery, M. K. (2020). Establishing the laboratory as the place to learn how to do chemistry. *Journal of Chemical Education*, *97*(6), 1511–1514.

Smallwood, Z. M., Campbell, C. D., Worrall, A. F., Cahill, S. T., & Stewart, M. I. (2021). Synthesis and evaluation of ammonia borane: A modular, multifaceted approach introducing experimental design through guided inquiry. *Journal of Chemical Education*, *98*(11), 3514–3523.

Smith, C. J. (2012). Improving the school-to-university transition: Using a problem-based approach to teach practical skills whilst simultaneously developing students' independent study skills. *Chemistry Education Research and Practice*, *13*(4), 490–499.

Smith, C. (2018). Education in Chemistry. In *Build students' confidence in their practical skills*. Royal Society of Chemistry. https://edu.rsc.org/analysis/build-students-confidence-in-their-practical-skills/3009741.article.

Spagnoli, D., Rummey, C., Man, N. Y. T., Wills, S. S., & Clemons, T. D. (2019). Designing online pre laboratory activities for chemistry undergraduate laboratories. In Seery, M. K., & McDonnell, C. (Eds.), *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton* (1st ed., pp. 315–332). Dublin: Creathach Press.

Supalo, C. A., Humphrey, J. R., Mallouk, T. E., David Wohlers, H., & Carlsen, W. S. (2016). Examining the use of adaptive technologies to increase the hands-on participation of students with blindness or low vision in secondary-school chemistry and physics. *Chemistry Education Research and Practice*, *17*(4), 1174–1189.

Trehan, I. R., Brar, J. S., Arora, A. K., & Kad, G. L. (1997). Fries rearrangement accelerated by microwave radiation in the undergraduate organic laboratory. *Journal of Chemical Education*, *74*(3), 324.

Turner, K. L. (2019). A framework to evaluate the transition to undergraduate studies in chemistry. In Seery, M. K., & McDonnell, C. (Eds.), *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton* (1st ed., pp. 9–22). Dublin: Creathach Press.

Wolkenberg, S. E., & Su, A. I. (2001). Combinatorial synthesis and discovery of an antibiotic compound: An experiment suitable for high school and undergraduate laboratories. *Journal of Chemical Education*, *78*(6), 784–785.

Wright, J. S., Read, D., Hughes, O., & Hyde, J. (2018). Tracking and assessing practical chemistry skills development: Practical skills portfolios. *New Directions in the Teaching of Physical Sciences*, *13*(13), 1–9.