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# Turning chemistry education on its head: Design, experience and evaluation of a learning-centred 'Modern Chemistry' subject

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## Abstract

In science courses in general, but especially in first year chemistry classes, the amount of content that is delivered is often overwhelming and too complex for the student to easily cope with. Students not only have to gain knowledge in a variety of different field, they also have to learn new laboratory skills and analytical techniques. Additionally, there is an issue with more and more information being available to everybody through the internet, while our education often still focusses on delivering that knowledge, rather than exploring ways how students can be guided to understanding and using the knowledge provided. There have been different approaches on how to make ‘dry’ scientific concepts more interesting and how enhance student engagement, ranging from problem-based learning approaches, case studies or flipped classroom models. We have recently turned a fairly classic first year chemistry course on its head. In the new structure, students are gaining knowledge and understanding purely through the completion of a range of challenges. We have removed all lectures, tutorials and the final exam, and all interaction with the student happens in the laboratory. Throughout the semester, students attempt to complete a range of challenges, both theoretical and practical, find relevant information, propose approaches to solving the challenges, and discuss these and subsequent outcomes with academic staff. In order to analyse the design, we have conducted structured interviews with students from 2016-2018. Initial assessment of the data suggests a high level of engagement of the students, paired with a better preparation of students for their subsequent studies. Students enjoyed having the freedom to choose and design their own experiments. Additionally, students improved significantly in non-content related aspects such as time-management, organisation, planning and self-learning, with notable impact on their learning in higher years.

## Keywords

curriculum innovation, challenge-based learning, evaluation

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## Abstract

In science courses in general, but especially in first year chemistry classes, the amount of content that is delivered is often overwhelming and too complex for the student to easily cope with. Students not only have to gain knowledge in a variety of different field, they also have to learn new laboratory skills and analytical techniques. Additionally, there is an issue with more and more information being available to everybody through the internet, while our education often still focusses on delivering that knowledge, rather than exploring ways how students can be guided to understanding and using the knowledge provided. There have been different approaches on how to make ‘dry’ scientific concepts more interesting and how enhance student engagement, ranging from problem-based learning approaches, case studies or flipped classroom models. We have recently turned a fairly classic first year chemistry course on its head. In the new structure, students are gaining knowledge and understanding purely through the completion of a range of challenges. We have removed all lectures, tutorials and the final exam, and all interaction with the student happens in the laboratory. Throughout the semester, students attempt to complete a range of challenges, both theoretical and practical, find relevant information, propose approaches to solving the challenges, and discuss these and subsequent outcomes with academic staff. In order to analyse the design, we have conducted structured interviews with students from 2016-2018. Initial assessment of the data suggests a high level of engagement of the students, paired with a better preparation of students for their subsequent studies. Students enjoyed having the freedom to choose and design their own experiments. Additionally, students improved significantly in non-content related aspects such as time-management, organisation, planning and self-learning, with notable impact on their learning in higher years.

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## Introduction

Much chemistry education in universities remains enthralled by tradition. Academic staff deliver lectures, and tutors and demonstrators lead tutorials and teaching laboratory sessions to illustrate and confirm the theories and concepts presented in lectures. Students attend lectures, do exercises and complete laboratory reports. Student learning is assessed primarily through high stakes examinations and success rates are variable.

But times and contexts as well as students and perspectives on learning and teaching have changed and arguably outgrown this traditional model. In contemporary science courses in general, but especially in first year chemistry classes, the amount of content that is delivered is often overwhelming and too complex for the student to cope with easily. Students not only have to gain knowledge in a variety of fields, they also have to learn new laboratory skills and analytical techniques. It is often difficult for students to connect the fundamental concepts covered to any ‘real life’ scenario or application. The view of the ‘big picture’ is often lacking, even if the lecturer tries to convey this in a lecture, which is in most cases still the most common form of teaching. Additionally, there is an issue with more and more information being available to everybody through the Internet, while our education often still focuses on delivering content, rather than exploring ways that students can be guided to understand and use information readily available on their computer or phone.

There have been different approaches to try to make ‘dry’ scientific concepts more interesting and enhance student engagement, ranging across problem-based learning approaches, through case studies to flipped classroom models. It has long been shown in the literature (for example, Blumenfeld et al., 1991) that students are typically more engaged and learn more, if they identify themselves with the material they are studying. This can for example be achieved in a project-based teaching approach, where students work, often in groups, on projects of various sizes that put the curriculum in an everyday context.

To address issues of student engagement and learning, our innovation has turned a quite traditional 1st year general chemistry subject on its head. In the new design, students are gaining knowledge, understanding and skills purely through completion of a range of challenges. We have removed all lectures, tutorials and the final examination, and every student interaction happens in the laboratory. Student learning is no longer graded. Rather non-graded passes are awarded for completed challenges, and the students complete the subject by finishing a set number of challenges. Almost all assessment occurs orally in the laboratory environment through conversations with the laboratory demonstrators and academic staff. In response to a presentation about the design at a recent chemistry/chemical education conference, one audience member described the change as “a very brave experiment”.

This paper provides an account of the rationale for the redesign and a detailed description of the subject as implemented by the teaching team and as experienced by students. So far, the subject has been provided three times, once each in 2016, 2017 and 2018. Minor refinements and adjustments were introduced for each of the later offerings based on informal evaluation and feedback. The subject was formally evaluated in the later part of 2018. Summary findings from the evaluation clearly indicate that from the student perspective, as captured by one of the students interviewed as part of the evaluation, for most: “it was weird, but it worked”.

## Theories and concepts behind the making of Modern Chemistry: turning from teaching to learning

The underlying theory of action for the redesign was to address concerns about student disengagement from learning chemistry and the associated limited learning and success. There were many consequences in the subject not the least of which was a very poor success rate. The underlying hope was that a reformed curriculum and learning environment would provide a more engaging learning experience and enhance student motivation and learning. The anticipated outcome was to enhance student learning across affective, psycho-motor and cognitive outcomes.

Our thinking about the shape of the reformed subject was guided by ideas from the specific chemistry education literature and the wider higher education learning and teaching literature. The concerns and criticism about student learning from chemistry laboratory experiences presented by Domin (1999) reflect a wider shift in thinking about curriculum, teaching and learning with the focus moving from teaching to learning (e.g., Biggs 1996, 1999, Banathy 1999). Biggs (1996, 1999) laid out the principle of ‘constructive alignment’ which has been refined (Biggs and Tang, 2007) and broadly applied as a fundamental concept of course design and development throughout recent years (see for example Angelo, 2012). His writings point to the critical importance of carefully considered design as a precursor to engagement with students. He advocated careful design thinking about the alignment of intended learning outcomes, assessment and learning experiences - ‘what the student does’ - to create a learning environment to encourage students to construct meaning and achieve higher order learning outcomes. His arguments are echoed by discussions in the chemistry education literature around the actual and potential contribution of traditional lectures and laboratory teaching to meaningful learning by students (Rice et al., 2009) and the interactions between elements of the experience that might promote or limit meaningful learning.

Prideaux (2003) briefly outlines the basics of curriculum, identifying what he labelled the three levels of curriculum: the planned curriculum, the delivered curriculum and the experienced curriculum. These categories provide a useful starting heuristic for thinking about reforming and the curriculum. However, Prideaux’s representation and labelling of ‘levels’ suggests some unarticulated hierarchy between these manifestations of the curriculum. We chose to consider each of these as a ‘state’ of the curriculum: each is different but sits beside the others and they interact with each other. Also, his representation tends to focus centrally on what the staff do – teaching, whereas we chose to focus primarily on the experienced curriculum: the student learning process (supported but not created by staff). Recognising that curriculum has (at least) three co-existing states, also helped us in subsequent evaluation to focus data collection, analysis, interpretation and use towards the best points to leverage improvements.

**Table 1**. Aspects of the curriculum

| The **levels** of curriculum (Prideaux, 2003) | The **states** of curriculum |
|---|---|
| Planned – as intended by designers | Planned – as intended by designers |
| Delivered – as taught by staff | Implemented – as *facilitated and guided* by staff |
| Experienced – learned by students | Experienced – as *learning* by students |

Exploring the literature on the limitations of the experienced curriculum in traditional chemistry education provided clear insights into a better planned and implemented curriculum.

### *Limitations of traditional Chemistry laboratory teaching*

*'Lectures and labs, lectures and labs …. Hands on, minds off'*

The teaching laboratory has been an integral part and signature pedagogy of Chemistry education for over a century. Debates about the characteristics of laboratory experiences, their goals and learning benefits have ebbed and flowed but persisted for almost as long without resolution: the question of its role in developing 'attitudes of mind' was raised in 1915 (Sandi-Urena, 2011 citing Spear, 1915). However, these debates have prompted waves of change, experimentation and innovation attempting to enhance the student experience and learning outcomes from laboratories. Domin (1999) developed a taxonomy of styles of chemistry laboratory teaching using three dimensions to characterise four dominant styles. The most common – expository/confirmatory – is also the most criticised with regard to learning benefit: the principal criticism is that the 'cookbook' type experience where students are required to follow experimental processes detailed in a laboratory manual result in 'hands on, minds off' behaviours from students with 'virtually no meaningful learning' (Domin, 1999, 544). A repeated theme in the literature is that support for the teaching laboratory has been based on strong belief and very limited evidence (Rice et al., 2009; George-Williamson et al., 2018). The research has consistently supported the view that the benefits from traditionally styled laboratory experiences are very limited (Schmid et al., 2019).

*Exploring alternative approaches to teaching and learning in chemistry laboratories*

In his review of laboratory teaching practices Domin (1999) noted that alternative approaches to teaching laboratories had been explored since the 1960s. While named differently and providing differing levels of freedom for students, various approaches had shared common characteristics of increasing student control over the learning experience and bringing the laboratory experience closer to 'doing chemistry' as problem solving and exploring challenges. Challenge-based teaching approaches offer the benefit that ownership of the learning experience is put into the hands of the student. In a typical approach, students will be exposed to a problem or challenge and through attempting to solve this problem, students not only develop problem solving skills and strategies, but also discover content knowledge. Challenge-based teaching approaches lend themselves very much to a flipped classroom model, where students work in teams to tackle the problems they need to solve. However, in most cases these teaching approaches are limited to more theoretical concepts and not necessarily to laboratory exercises. The literature increasingly includes examples incorporating challenge-based laboratory experiences into chemistry subjects. These are predominantly small-scale interventions within traditional structures (George-Williams, 2018; Szteinberg et al., 2013; Sandi-Urena et al., 2011; Winkelmann et al., 2015).

The approach fosters and promotes self-directed and peer-assisted learning over classical accumulation of knowledge. While the curriculum is less broad in terms of topics covered, students get a deeper understanding in a selected number of areas. Additionally, students are encouraged to become more independent learners. All this focuses on preparing our graduates for their future, when they will be applying for jobs that today might not even exist.

## The Modern Chemistry design and experience

Modern Chemistry is a second semester, first year general chemistry subject. Enrolment numbers are between130 and 150 students per subject offering. It is one quarter of a full time study load. Modern Chemistry caters mainly for students that study a major in chemistry, including degrees in nanotechnology or forensic and analytical sciences. A significant number of students also have a more biology-oriented background and some students in the subject study health sciences or related degrees. Some students are enrolled in double degrees in Education and Chemistry with some of them having never studied Chemistry before. Its educational aims are to:

- Reinforce and expand upon final year high school (Year 12) Chemistry curriculum (in South Australia) while introducing students to new areas of chemistry
- Together with related higher year subjects, provide students with the full complement of theoretical and practical skills that are essential to a career as a professional chemist
- Provide the necessary grounding in basic chemistry for students who will eventually major in other disciplines
- Explore modern methods of molecular identification, redox and organic chemistry, kinetics and physical chemistry
- Prepare students to undertake higher year studies in chemistry.

The stated intended learning outcomes are that at the completion of the subject, students are expected to:

- Develop independent study skills
- Have a sound knowledge of the material delineated by the subject description statement
- Develop useful generic and scientific skills in Chemistry and start to develop chemical intuition for type of reactions or chemical transformations that might occur
- Develop skills in handling chemicals, apparatus and instrumentation and, by working together with other students, will begin to develop teamwork and problem-solving skills in addition to strengthening their own self-learning skills
- Develop communication skills, skills in solving problems and build on their self-confidence.

While these aims and learning outcomes are not a radical shift from the generally advocated educational intentions for such subjects (Bruck, Towns and Brett, 2010), the innovation focused on radical change to the means to achieve them and fundamental shifts in the design of the assessment of student learning.

As noted previously, the redesign marked a major shift away from teaching to learning. In the first offering of the subject there were no lectures. In more recent offerings, one lecture has been provided at the start of the subject not to give chemistry content knowledge but rather to introduce students to the structure of the learning experience and to the requirements to successfully complete the subject.

## Challenging students and assessing achievement

The subject is built around 14 challenges (Table 2), and students must pass all challenges in order to receive a pass grade overall (non-graded pass). For each challenge, there are various options and alternatives the students can choose from. Every challenge requires substantial out of class work where students explore theories, concepts and processes before attending formal scheduled learning sessions in the laboratory.

**Table 2.** Overview of the different concepts used in the various challenges. Students have to complete all white, all yellow and two black challenges.

| **White Challenges** | **Yellow Challenges** | **Black Challenges** |
|---|---|---|
| Colour and electron transitions | Buffer; Acid/Base chemistry | Organic synthesis |
| Separation of molecules, organic chemistry | Crystallisation | Water analysis |
| Acid/Base chemistry | Organic synthesis | Natural Product extraction |
| Thermodynamics | Natural Product extraction | Polymer chemistry/ Electrochemistry |
| Electrochemistry | Analytical Chemistry | Analytical Chemistry, bio-organic chemistry |
| Bio-organic chemistry | | Analytical Chemistry |
| Applied Chemistry | | Polymer Chemistry |
| | | Physical Chemistry |

In seven theoretical challenges ('white' challenges), students explore fundamental concepts. They work in pairs (or individually if they choose) and answer questions that are designed to elaborate on specific aspects of the curriculum. The pairs are not assigned, and students are encouraged to choose their own partners. All questions are deliberately kept relatively open ended. For example, when assessing the concept of colour, electron configuration and the relationship between energy transitions, absorption and wavelength, we ask the students the question: "why is Mars red?" A quick Internet search will reveal that Mars is red because its surface consists largely of iron oxide. Once the student gives that answer, we will ask the follow-up question, why is iron oxide red? This leads to discussion of the quantum nature of energy levels which is one of the fundamental concepts in first year chemistry. All challenges are designed to lead students to discover such fundamental concepts as opposed to being told them.

All formally programmed face-to-face interactions between students and staff happen in the laboratory and all assessment is done orally. In a typical laboratory session, one academic staff member and four demonstrators worked with up to 50 students. The demonstrators were postgraduate research students who were carefully selected and trained for the subject. Additional resources for the students were made available through the learning management system.

Students can attempt challenges in any order. They choose a challenge and a question for this challenge and research for answers. Once a student thinks they have found an answer to a question, they talk with an academic or demonstrator about it, who assesses whether there is enough understanding shown or whether additional research is needed. Academic staff and demonstrators did agree on some guidelines on how to judge whether a student had sufficient knowledge and understanding. These interactions can range from 1 minute to about 10 minutes, and often include individual coaching and tutoring of the students. This allows a personalised approach as different background knowledge and different levels of understanding can be catered for and the students can choose how to present their results. The non-graded pass for the assessment allows staff to work with students of various levels. It guides weaker students to a threshold learning level and very strong students beyond their boundaries.

In most cases, students came with some initial findings about a certain question, and could answer a few follow-up questions, but were lacking a few details. In these cases, the instructor would formulate a few specific, more detailed questions for the students to further research. Once they had done this, they could continue the discussion (with the same or a different instructor) until they have shown adequate understanding of the concept. For this process to be possible, a documentation process was set-up within the learning management system (LMS), where every student-instructor interaction is documented, and hand-over notes for follow-up discussions are kept much like having charts for patients in a health care setting. Again, the non-graded pass system allowed for a personalised approach, where each assessment or each question was tailored to the individual student.

In addition to the theoretical challenges, the students also complete seven practical ('yellow') challenges. Five of these challenges are done individually and focus on the development of critical laboratory skills such as titration, pipetting, preparation of solutions, synthesis, and data analysis. Again, students are given some flexibility and freedom. Within the broad concept of a challenge, the student has to develop their individual approach. The student prepares a proposal, where they outline their experiments, specify needed chemicals (often with set limits) and potential associated risks. Once this has been approved by a demonstrator, they perform the experiments, analyse the outcomes and, if successful, pass the challenge. If the outcome is not successful, they have to repeat the experiment. The idea is for them to do an experiment, until they do it correctly. For example, one challenge involves the synthesis of an ester, and reactants can be selected from a prescribed list. The challenge is completed once the student can prove that their product is the ester they intended to make. This is typically done through an adequate chemical identification technique. Especially for these challenges, the non-graded pass is the best assessment approach. When learning and mastering a skill, it does not make sense to accept partial completion. Similar to approaches used in medical education, we adopted a strategy where students have to show mastery of a certain skill to pass the subject. When, for example, they have to determine the concentration of a solution, there is only one correct answer. Students could only pass the challenge if they could name the correct value. Similarly, when the task is to synthesise a certain molecule, there is only one correct outcome.

The remaining two ('black') experimental challenges are done in groups of up to four students and are designed to be larger projects that can span multiple weeks. Again, there is a selection of topics that students can choose from, and in the design of these projects we have tried to cater for the diverse range of courses and interests the students have. There are challenges that are more appealing to students with more synthetic interests, while others have more of an analytical or even technological focus. These final group challenges are more complex, longer with more involved experiments, where students go through the entire process of designing an experiment, deciding on how to analyse their results, and finally collate, discuss, evaluate, and present their findings.

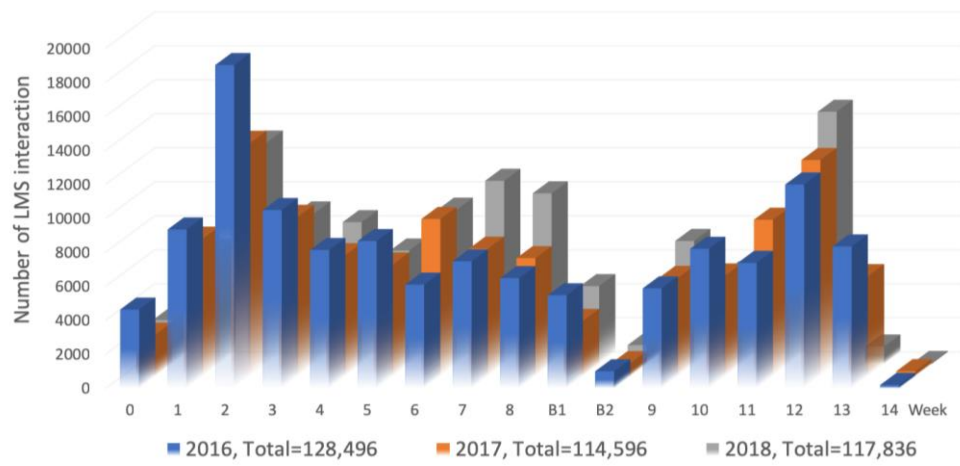
## Improving the design from experience

The redesigned subject has now been offered three times in 2016, 2017 and 2018. In the first year, it became apparent quite quickly that time management would be a major issue for most students. Most students struggled with the idea of having to organise themselves, having to decide which experiments to do and when and where to put effort into the subject.

In 2016, a lot of students finished all challenges at the last possible minute, even with extra time allowed. This issue has been addressed in subsequent years by making students aware of the time management problem from the beginning. Most helpful were video recordings of students from the previous class saying that time management was a crucial factor in succeeding in the subject. The number of students that struggled to complete has since significantly reduced. This is also evident in analysis of the student interactions with the learning management system (Figure 1). Since every student/demonstrator or student/academic interaction is recorded in the LMS, an analysis of the

LMS usage gives a good indication about when students did most of the work. In 2016, a large fraction of the students still did a lot of work in week 13, even though we had intended that they finish after 12 weeks. In contrast, in 2018, hardly any students still had to do work in week 13.

***Figure 1.*** Analysis of the use of the LMS in the subject. Number of LMS interactions as a function of semester week, including 2 weeks of a mid-semester break (B1 and B2).[1]




Other small improvements after the first offering/iteration were the introduction of a more structured pro-forma for students to propose experiments, which provided more guidance and ensured that essential parts of the proposal such as reaction equations, quantities, and safety issues are always addressed.

Additionally, the set-up of the laboratory has been adapted, with a lot of glassware and standard chemicals now being freely available to students, which eased the burden on the laboratory staff for preparation before the practical sessions. Stocking shelves with the most commonly used chemicals has been the single most significant time-saving change. While planning their experiments students are encouraged to check for available chemicals, not unlike as would be the case in a research or industry lab. Only if they require additional material do they fill in an order form and seek approval from an instructor.

### *Summary of key design aspects*

In summary, the curriculum design and experience have been built around specific changes:

1. Laboratory experiences are at the centre of the student learning experience supported by extensive resources in the university's learning management system and interactions with staff in the laboratory. Lectures are no longer the central teaching method.

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[1] In B1, an additional laboratory session was offered. The university has 12 official teaching weeks in the corresponding semester.

2. Oral assessment to probe and confirm student learning has replaced examinations and other written assessment tasks. This is a deliberate attempt to counter 'hands on; mind off' behaviours of more traditional written assessment where students could/would write up what they had done without knowing what had happened or why.
3. Student learning in the subject is recognised through a non-graded pass to deter mark seeking behaviours and to encourage students to focus on learning about chemistry and doing chemistry.

The subject has been fundamentally re-oriented to focus on what the student does, to give them greater control over their learning. Minor adjustments have been made along the way in response to informal student feedback and observations of student behaviours. The subject has also been formally evaluated to systematically explore student responses to the 'brave experiment'.

## Evaluating our 'brave experiment'

Earl and Timperley (2015, p10) note "the idea of educational evaluation is deceptively simple". Evaluation methods and thinking are tools for systematically gathering and interpreting information that can be used to provide feedback loops for refinement, adjustment, abandonment, extension and new thinking about educational interventions. But evaluation is contested and challenging in practice (Nevo, 1982; Leathwood and Phillips, 2000; Stavropoulou & Stroubouki, 2014).

Nevo (1982) still provides a useful guide to the conceptualisation of educational evaluation. His review of the dimensions of educational evaluation is structured around ten questions. He suggests "[e]valuators could use the 10 questions to organise their own perceptions of evaluation… to develop their own set of coherent answers" (p. 126). Our definition of evaluation in response to his first question was broad: evaluation is a systematic process of information gathering to inform judgements about educational interventions. Our answers to the nine (slightly reformed) design-focused questions are summarised in Table 3. These answers shaped our approach to the formal evaluation of 'Modern Chemistry'.

The main focus of the evaluation was the experience of students in the laboratory doing Modern Chemistry (Table 4). We were interested in both patterns of responses across student cohorts and individual stories of the experience.

The students' stories of 'doing Modern Chemistry' emerged from semi-structured interviews. 38 students took part in interviews. Participants were drawn from across the three cohorts that had undertaken the subject since the new structure was introduced in 2016: 14 from the 2016 cohort, 14 from 2017 and 10 from 2018. All interviews were done by the same member of the team, recorded and transcribed. The interviews lasted between 35 and 60 minutes.

**Table 3.** Design of our evaluation approach

| | |
|---|---|
| What are the functions of our evaluation?<br><br>Summative<br>Formative<br>Socio-political<br>Administrative | The functions of our evaluation encompass<br>1) summative: To determine the influence of the redesigned subject on the student experience and learning outcomes across 2016-2018 offerings of the subject;<br>2) formative: to identify opportunities for improving the student learning experience;<br>3) socio-political: to influence the practice of chemistry laboratory learning more broadly.<br>The evaluation was also intended to serve an administrative function as part of reporting on a fellowship grant which supported the initial curriculum redesign. |
| What are the objects of evaluation? | The evaluation focused on the 3 curriculum states – design, implementation and experience - of the subject with major focus on implementation & student experience. |
| What kinds of information were collected regarding each object? | Formal documentation of the curriculum as designed;<br>Student reflections on their experiences via semi-structured interviews;<br>Laboratory demonstrator accounts of their experiences via journals;<br>Academic staff accounts of their experience via journals;<br>Quantitative data on student engagement and success rates across the three offerings. |
| What criteria are used to judge the merit and worth of an evaluated object? | Has it made student experience better in relation to intended learning outcomes (see below) and by comparison to traditional subject design? |
| Who should be served by our evaluation? | The immediate beneficiaries are the teaching team involved in the ongoing improvement – provided with information and insights to inform future developments. Also students in subsequent offerings/availabilities of the subject. Beyond these key beneficiaries, others involved in the enhancement of student learning hopefully will benefit from our accounts of what came from the evaluation – our descriptions of and judgements about the effect of the experience on student learning.<br>Also, the funders of the fellowship to enable decisions about the effectiveness of the grant to encourage sustainable curriculum innovation. |
| What is the process of doing the evaluation? | Interviews, journals, analysis & coding leading to rich descriptions and conceptions of 'doing Modern Chemistry' to give feedback/feedforward to designers and teaching to inform future refinements. |
| What methods of inquiry were used in evaluation? | Primarily qualitative journaling and interviews capturing the voices of participants. These methods enabled us to capture narratives and identify conceptions of 'doing Modern Chemistry'. |
| Who did evaluation? | The evaluation team included:<br>The teaching team, including laboratory demonstrators;<br>An independent research coordinator who conducted student interviews;<br>An academic developer with approximately 40 years' experience in educational evaluation who guided design of the evaluation, analysis of the data |
| By what standards should the evaluation be judged? | The fundamental standards for judgement are whether the evaluation has been conducted systematically to provide usable information to judge the worth of the innovation and to identify further opportunities to enhance the student experience in the subject and beyond |

The students' stories were analysed through careful coding and interpretation to identify the prevalence and strength of key themes and concerns and opportunities for improvement: the 'stand out' factors in their recollections and recounting of 'doing modern Chemistry'. A sample of transcripts were independently coded by two members of the team. Initial codings were discussed and compared for consistency. A composite set of agreed codes were used to code all transcripts. We anticipate providing fuller narratives of experience in later publications; here we focus on quantitative patterns of responses across the participants.

**Table 4.** key themes extracted from interview transcripts. The numbers represent the number of interview participants who provided comments coded against a particular code within an overarching category.

| Category | Code | 2016 N=14 | 2017 N=14 | 2018 N=10 | Total N=38 |
|---|---|---|---|---|---|
| **Confidence** | Improved confidence | 8 | 8 | 6 | 22 |
| **Enjoyment** | Enjoyed it | 6 | 7 | 3 | 16 |
| | Fun | 7 | 7 | 3 | 17 |
| | Good | 8 | 4 | 6 | 18 |
| **Freedom** | Liked being in control of own learning | 12 | 12 | 7 | 31 |
| **Group work skills** | Group work helped learning | 3 | 6 | 6 | 15 |
| | Group work led to better work through diversity | 6 | 6 | 6 | 18 |
| | Liked group work | 11 | 7 | 6 | 24 |
| **Building relationships** | Built relationships with peers | 6 | 3 | 4 | 13 |
| | Liked developing friendships | 3 | 4 | 5 | 12 |
| | Built relationships with staff | 5 | 1 | 5 | 11 |
| **Future learning** | Helped with other subjects | 11 | 13 | 2 | 26 |
| **Learning approach** | Difficult to know how/where to start | 3 | 5 | 4 | 12 |
| | Felt thrown in the deep end/self-directed | 7 | 9 | 6 | 22 |
| | Fostered independent learning | 5 | 7 | 5 | 17 |
| | Learning why & how | 8 | 4 | 3 | 15 |
| **Challenges** | Achievement focus | 5 | 7 | 6 | 18 |
| | Guidance on when to do challenges | 3 | 3 | 6 | 12 |
| **Non-graded pass** | Didn't mind non-graded pass | 5 | 3 | 7 | 15 |
| | Non-graded pass took pressure off | 7 | 3 | 4 | 14 |
| **Oral assessment** | Liked orals | 4 | 4 | 8 | 16 |
| | Orals allowed demonstration of learning | 7 | 8 | 8 | 23 |
| | Orals helped with learning | 7 | 11 | 6 | 24 |
| **Structure** | Liked the structure | 6 | 2 | 6 | 14 |
| | Would have liked more guidance | 7 | 10 | 7 | 24 |
| **Time management** | Concern re rework | 3 | 5 | 6 | 14 |
| | Concern with time management | 7 | 7 | 5 | 19 |
| | Improved time management | 4 | 8 | 3 | 15 |

The clearest indication from the data is that most students (31/38) liked being in control of their own learning and some commented explicitly that the experience fostered independent learning. Also, for a large number the experience improved their confidence. Words around enjoyment and fun recurred through many transcripts as did positive comments on the social aspects of the learning experience including group learning (24/38) and building relationships with peers and staff.

There were, nevertheless, some repeated concerns about the approach and structure, with students uncertain how to start and feeling ‘thrown in the deep end’ (22/38). There was a widespread call for more guidance particularly on the process and time management through the subject.

The main structural elements of the subject – the challenges and oral assessment – attracted predominantly positive comments. Students commented positively on the ‘achievement focus’ created by the challenges, although some expressed some concern about re-work, that is, the expectation that students had to re-do experiments until they were right! Galloway et al. (2016) advocate for opportunities for students to critically analyse the possibilities and make choices without fear of penalty and argue ‘Laboratory work ought to encourage cognitive exploration by asking ‘why?’ without negative consequences’ (p.236). In Modern Chemistry students were encouraged to ‘ask why’ with minimal negative consequences, that is, the need to spend additional time revisiting the question if they did not get it right the first time. Similarly, students made positive comments about oral assessment in the subject noting that it helped with learning (24/38) and provided an effective way for them to show their learning (23/38). As one student commented: “you couldn’t fake it; you had to know to be able to convince demonstrators to sign off – a better way to demonstrate learning”.

However, the approach was not universally welcomed. One interview participant completely rejected the whole learning approach. The student, who self-identified as a high achiever in their previous studies, was embedded in tradition: needing to be taught content before being able to apply it. The learning-centred design was completely alien to them. The student chose to employ an external tutor to teach content before the student could tackle the challenges. The challenge-based design for this student – and perhaps others – was an overwhelming threat to learning rather than an opportunity for learning.

In contrast, some students explored/extended themselves into new challenges beyond those suggested, proposing and successfully conducting complex experimental procedures: not even contemplated let alone possible in traditional expository teaching laboratories. The variety of responses to the learning approach echoes the findings of Galloway et al. (2016, 236) that ‘some students desire to be Challenged [sic], while others fear it.’ The responses from our participants also resonate with the findings from research by Sandi-Urena and colleagues (2011) which found that students moved along a trajectory from discomfort, shock and confusion - due to unfamiliarity with what was expected - through resistance to acceptance of the new reality and, in some cases, to pushing the boundaries of the new experience. Some students were not willing or able to move beyond discomfort and resistance but the majority moved to acceptance and enjoyment of the offered experience.

The most appropriate level of guidance and structure/signposting to provide for students is difficult to determine. The contrasting student views about control and freedom compared with the need for guidance suggest students need less rather than more but still a little more than they get now. Both students and staff identified the need for signposts/milestones to help students gauge and keep on top of their progress. More signposting also has potential to alleviate a key problem: having to deal with ‘stockpiled’ work was a concern for both students and demonstrators. For students it meant having to wait for a demonstrator to be available to mark off their completed work; for demonstrators it meant that in some sessions towards the end of the semester they were so absorbed by trying to clear the backlog to help students complete, that they felt they were not able to provide 'enough' support to students still completing experimental work.

Student experience and achievement of the intended learning outcomes of the subject are the key measures of the success of our innovation. In summary, the data from the evaluation suggests the experience in relation to the learning outcomes:

1. provided opportunities through in particular the white challenges to 'develop independent study skills'.
2. required students to have a 'sound knowledge of the material delineated by the subject description': without such knowledge students could not pass the challenges or the topic. The oral assessment strategy assured this.
3. provided repeated opportunities through the yellow and black challenges for students to 'develop useful generic and scientific skills in Chemistry and start to develop chemical intuition for type of reactions or chemical transformations that might occur'
4. required students to 'develop skills in handling chemicals, apparatus and instrumentation' and, by working together with other students, 'begin to develop teamwork and problem-solving skills'. It is notable that a large majority of participants (24/38) liked the group work aspect of the experience and that it was seen as having a positive effect on learning by approximately half of the participants.
5. enabled students to 'develop communication skills, skills in solving problems and build on their self-confidence'.

Notably, the vast majority of participants from the 2016 and 2017 cohorts (24/28) stated that their experience of 'doing Modern Chemistry' had helped them with other subjects, with comments identifying familiarity with the laboratory environment and equipment, being prepared to take initiative and generally improved confidence. One participant noted "I think it helped with my critical learning and kind of self-direction, self-motivation, which can really be applied to anything". This is however an area that highlights a limitation of the evaluation. While participants identified an array of benefits that they carried over to other subjects, the evaluation did not seek the views of staff teaching in subsequent chemistry subjects taken by participants. While some demonstrators in senior year subjects commented on improved student preparedness, some anecdotal indications suggest that some staff teaching in later year subjects did not share the same positive view on the benefits of the experience to students. This is a potential area for later research.
It is also noteworthy that, while changes to the subject learning outcomes were not part of the redesign, the evaluation has suggested the need to revisit and redefine the learning outcomes to increase clarity and precision.

## Conclusion and implications

As has been argued elsewhere, (Houston, 2004) seeing a curriculum as having multiple coexisting states can help to focus evaluation and improvement activities. From this perspective a curriculum is like a bridge to learning: a curriculum, like a bridge, should ease the journey to learning for students, should have structural integrity and should fit its environment. A curriculum, like a bridge, has multiple states: it is designed, constructed, and experienced by students as learners. A systemic perspective on curriculum and design for learning (Banathy, 1999; Houston, 2004) helps to ensure that the elements and states of the curriculum align as closely as possible to ensure the best possible journey to learning for students. If evaluation of the student experience identifies opportunities for improvement, these need to be incorporated into the design and implementation to provide the basis for an enhanced student experience.

Rice et al. (2009) note the critical need to include assessment – as a major driver of student behaviour - in evaluation and redesign of laboratory experiences. Assessment reform has the potential to shift student attention from getting the highest mark to increasing learning. They reiterate the importance of alignment of assessment with intended learning outcomes and what the student does, and the need to explore the whole constellation/complex system of elements and interactions towards improving the student learning experience in the laboratory learning environment. The redesign of Modern Chemistry encompassed the whole network of elements in the curriculum, with particular attention to what the students do and how it is assessed. Participant responses clearly identified the effects of the removal of grades and the introduction of oral assessment: both the intention and the student reactions positioned assessment as integral to learning and as a prompt for learning.

Over multiple offerings of Modern Chemistry, some refinements had been made in response to student comments about the nature of their learning journey. Some of these had resolved underlying issues while others had alleviated symptoms. The formal evaluation has shown that the subject provides an experience where the students are in control of their learning and that the majority enjoyed the freedom given to them. However, some did not, finding the challenge created by the approach too much and too different from their previous experiences. Notably, even those who liked the experience wanted more guidance and structure particularly around managing time.

More work may be needed to create an environment where the space to experiment and explore is more bound and guided for those who need it. Nevertheless, the ‘brave experiment’ has shown that careful design can frame an experience that is fun and enjoyable for students and that also supports students to learn across cognitive, psycho-motor and affective outcomes.

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