Chemistry Education Research and Practice

ROYAL SOCIETY OF CHEMISTRY

PERSPECTIVE

View Article Online
View Journal | View Issue

Cite this: *Chem. Educ. Res. Pract.*, 2024, **25**, 383

Received 6th September 2023,
Accepted 26th November 2023

DOI: 10.1039/d3rp00245d

rsc.li/cerp

10 Guiding principles for learning in the laboratory

Michael K. Seery, *[a] Hendra Y. Agustian,[b] Frederik V. Christiansen,[b] Bente Gammelgaard[c] and Rie H. Malm[b]

Laboratory work in chemistry has been extensively researched in the last decade but the gap between research and practice is still broad. This *Perspective* shares 10 guiding principles relating to university laboratory education, drawing on research over the last decade. Written with an audience of practitioners in mind, the *Perspective* aligns with Hounsell and Hounsell's congruence framework, so that the 10 principles consider all aspects of the laboratory curriculum: design, teaching approaches, and assessment approaches as suggested by Biggs, but additional contextual factors relating to teaching context: backgrounds of students and their support, and overall laboratory organisation and management. After discussing the rationale for each guiding principle, examples of approaches are given from recent literature along with prompts to help enact the guiding principle in practice.

Introduction

It has been a productive decade for research on teaching and learning in chemistry laboratories. Major programmes of activity have reported conceptualising the laboratory as a space for meaningful learning (Bretz *et al.*, 2013), discussion of intended goals (George-Williams *et al.*, 2018b; Seery *et al.*, 2019b; Agustian *et al.*, 2022a), reassertion of the role of preparation activities (Agustian and Seery, 2017), incorporation of more opportunities for experimentation (Seery *et al.*, 2019a; 2019b; 2019c; Gorman *et al.*, 2021), teaching and learning of practical skills (Towns *et al.*, 2015; Hensiek *et al.*, 2017; Seery *et al.*, 2017), better consideration of learning in advanced practical settings (Schmidt-McCormack *et al.*, 2017), an in-depth exploration of lived experience of students in laboratory contexts (DeKorver and Towns, 2015; DeKorver and Towns, 2016; Galloway *et al.*, 2016; Jørgensen *et al.*, 2023; Finne *et al.*, 2023) and a renewed emphasis of consideration about the purpose of practical work (Bretz, 2019; Seery, 2020) – the latter caused in no small part by the COVID-19 pandemic (Kelley, 2021). These have all combined to give extensive insight into designing, teaching, and assessing the laboratory component of chemistry curricula.

While those researching learning in laboratories can be glad of this renewed interest and extensive outputs, the predominance of the pandemic in overwhelming much of the discourse relating to learning and teaching means that much of this research into laboratory education may not yet have influenced teaching practice. The laboratory literature – already vast – has swollen further in the last decade, with substantial progress in our understanding of laboratory learning environments and students' experience of them. This *Perspective* aims to bring a summary of sorts to this past decade – and the learning we can take from it – in a format useful to the broader community of educators. Connor and Raker (2023) recently argued that there is an onus on chemistry education researchers to work with practice-focussed colleagues and support their engagement with evidence-based practices. Conscious of the challenges of bringing research into practice, we share these outputs by parsing them in the form of "Guiding Principles" for those who are interested in developing or redeveloping their laboratory curriculum and activities. This approach has been successful elsewhere in furthering awareness, dialogue, and action on educational reform (Nordmann *et al.*, 2020). We purposefully remain agnostic to particular laboratory teaching approaches such as those shared by Domin (1999) (inquiry, problem-based, *etc.*), instead preferring to share suggestions grounded in more general terms. This is partly because faculty may have preconceptions about particular approaches that override the actual teaching and learning principles that underpin them, but more generally because the reality of change is often incremental; changing aspects of laboratory teaching is often more achievable in small iterations than making overall systemic change aligning to a particular paradigm all at once (Mundy *et al.*, 2023). Different actors involved in laboratory work will have different amounts of resource, power, and time

[a] *Quality Enhancement Directorate, Cardiff Metropolitan University, Cardiff CF5 2YB, UK. E-mail: mseery@cardiffmet.ac.uk*
[b] *Department of Science Education, Faculty of Science, University of Copenhagen, Denmark*
[c] *Department of Pharmacy, Faculty of Health and Medical Sciences, University of Copenhagen, Denmark*

to make change. Our guiding principles aim to address laboratory teaching from design through to assessment and reflection on learning, and aim to be as informative as possible to all those who may have some capacity to engage with them.

Therefore we intend to address the question "*What should those involved in laboratory education know from recent research about laboratory curriculum design and implementation?*" The remainder of this perspective describes our answer to this question.

Constructive alignment and congruence

Biggs has described well the consideration of teaching, learning, and assessment in any situation by prompting educators to think about (i) what it is they want students to learn, usually written as learning outcomes; (ii) how the teaching and learning activities they engage students in will help students achieve those goals; and (iii) how assessment will effectively determine the extent of learning (Biggs, 2003). Consideration of these three aspects in tandem and ensuring that they are in agreement is known as constructive alignment, and is one of the major tenets of curriculum design. An example where laboratory activity may not achieve constructive alignment is where a learning outcome may relate to some aspect of development of technical skills, the activity itself includes the teaching and use of those skills, but the assessment (such as a written report) does not effectively allow students to demonstrate these skills directly. Such a scenario is misaligned, leading to substantial repercussions on the effectiveness of the teaching scenario intended (DeKorver and Towns, 2015; DeKorver and Towns, 2016).

One of the long acknowledged challenges of laboratory education is coherence among educators involved in teaching students (Tremlett, 1972; Boud *et al.*, 1986), with the curriculum as intended differing from the curriculum as enacted. Acknowledging the challenge of learning contexts in general, as well as issues relating to curriculum implementation, Hounsell and Hounsell (2007) extended the constructive alignment framework to incorporate what they term 'contextual influences', to acknowledge the reality of variation in learning contexts in contemporary higher education. This weaves into Biggs' framework additional contextual considerations of (iv) student backgrounds and aspirations, (v) learner support, and (vi) course organisation and management, and advocates that there is 'congruence' between this array of dimensions to consider in teaching and learning environments (Fig. 1). The congruence framework places the learner at the centre of the learning process and intended outcomes, while reflecting the very real complexities associated with learning in laboratories in particular contexts. It has proved to be a useful framework for exploring the lived experience of students in laboratories (Jørgensen *et al.*, 2023).

In order to develop our guiding principles, we sought to ensure that the teaching goals, learning activities, and assessment protocols were aligned, but additionally to incorporate these additional factors identified by Hounsell and Hounsell to accommodate the lived reality for students in the particular context of laboratory teaching. This is especially important in light of previous writings on the disharmony in laboratory teaching approaches. For example, as well as ensuring alignment of teaching and learning activities with appropriate assessment, enacted practice could also consider how we support learners in engaging with those activities (through the use of pre-laboratory activities; our *Guiding Principle 3*), align with student backgrounds and aspirations so that learners can engage in a meaningful way (captured in our guiding principles relating to designing for inclusion of all students and their prior learning; our *Guiding Principle 1*) and embed opportunities for creativity (our *Guiding Principle 7*). In other words, we have used Hounsell and Hounsell's model to ensure our principles cover the various dimensions of curriculum they identify, and consequently promote congruence between these dimensions. They are presented as follows in the sequence of laboratory purpose and design (Guiding Principles 1–2), preparatory work and in-laboratory teaching and learning (Guiding Principles 3–7), and laboratory assessment, feedback, and reflection on learning (Guiding Principles 8–10).

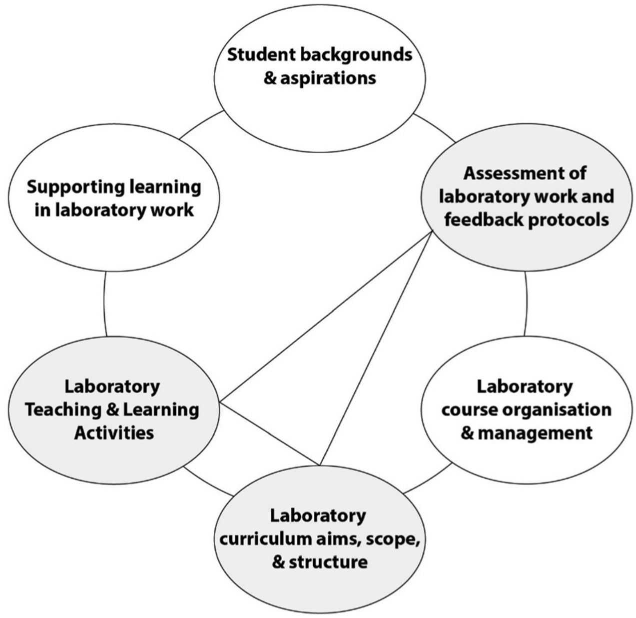

Fig. 1 Constructive alignment between intended curriculum outcomes, teaching and learning activities, and assessment of activities (shaded areas connected by triangle) is a useful approach to laboratory curriculum design; however the additional contextual influences to be considered prompt thought into how the curriculum can be enacted in specific contexts, ensuring congruence across the intended – and experienced – curriculum (based on Hounsell and Hounsell, 2007).

Guiding principles for learning in the laboratory

Guiding Principle 1: create laboratory environments that are accessible and conducive to learning

This first guiding principle draws from recent discourse about how we create accessible learning environments that are conducive to learning (Egambaram *et al.*, 2022); that is to say it focuses on a consideration of who the students in our laboratory courses are. Students entering our laboratory courses can bring (i) a broad range of prior knowledge, (ii) perceptions about laboratory learning, (iii) learning approaches they plan to adopt in the laboratory, and (iv) awareness of learning outcomes (Prosser and Trigwell, 1999). Much of modern educational discourse leans on the educational psychologist's David Ausubel's statement "*The most important single factor influencing learning is what the learner already knows. Ascertain this and teach [them] accordingly*" (Ausubel, 1968, p. vi). Bretz and coworkers extend this consideration to emphasise the role of meaningful learning in the specific context of the laboratory. As well as connecting new learning to students' prior knowledge, they advocate that meaningful learning occurs when learning materials are designed so that students can make connections to this prior knowledge, through facilitating their engagement with this content (Bretz *et al.*, 2013; Galloway *et al.*, 2016). This aligns well with Hounsell and Hounsell's advocacy of consideration of student backgrounds and aspirations (Fig. 1).

Tangible actions that can be taken to account for students' prior experiences are summarised in Table 1. The greatest diversity of prior knowledge in laboratory learning is likely to be when students first take up laboratory work at university, as there will be a broad diversity of prior experiences and competencies. Reviewing curriculum specifications at school level can give highly detailed information on the range of skills and competencies covered at school (for example, in the United Kingdom, see Read and Barnes, 2015, p. 38). Care is needed then to build in to early university work activities that can help students connect with prior knowledge and make the bridge to university work. Examples include highly structured activities for those new to chemistry and with little prior laboratory experience (Spagnoli *et al.*, 2017), a bridging course in advance of the formal laboratory work to introduce the university laboratory experience (Spencer-Briggs and Rourke, 2023), and guidance to support students moving from one education system to another (Hyde *et al.*, 2023). One of the most common challenges relates to helping students learn about common laboratory skills that may have been taught to varying levels (or not at all) in prior education, and structured activities that focus on learning these skills (rather than the associated experiments that use them) have proven to be valuable (Towns *et al.*, 2015; Hensiek *et al.*, 2017; Seery *et al.*, 2017). These variations in student experiences are most obvious at the beginning of undergraduate education, but similar principles apply throughout their studies. Those involved in teaching laboratory work at each stage should consider what students' prior experiences were, and whether there is variability in those experiences, so that learner support can be planned as needed.

As well as diversity in laboratory competencies based on prior experiences, there will likely be other diversities among student cohorts, and therefore laboratory work should be designed to ensure it is accessible to all students, and staff (Egambaram *et al.*, 2022). Flaherty recently discussed sensory overload in laboratory environments (Flaherty, 2022), which highlights several considerations that could enhance the learning experience for neurodivergent students, but in fact offer good design principles for *all* students. This concept of universal design – preparing learning environments so that they are accessible to all students rather than the need to accommodate particular student needs on a case by case basis – is gaining substantial momentum and has previously been outlined for laboratory settings by Miller and Lang (2016). Universal design approaches for laboratory teaching that facilitates students who are blind or have low vision have also been described, emphasising the use of accessible materials and incorporation of tangible models and text-to-speech instrumentation (D'Agostino, 2022). There is extensive work on pedagogical approaches of d/Deaf and hard of hearing students, with suggested technologies including chat/instant messaging facilities to complement verbal dialogue (Pagano and Quinsland, 2007). Universal design approaches intend to move away from a "deficit" framing of students and their abilities, and instead introduce approaches that can be of benefit to all learners. Such approaches have ongoing benefits, such as supporting students who may be studying in a second language. Hyde describes the use of photographs with English and Chinese labels used in laboratory teaching materials to help learners identify instrumentation and learn the term for them, as well as allowing for students to take and use photographs of explanations and experimental set ups that they could use for follow up questions or in their own study (Hyde, 2019). General

Table 1 Actions to take to align with *Guiding Principle 1* and associated exemplary practices from the literature

Action	Examples
Review school curricula or other pre-requisite/co-requisite learning to ensure alignment with intended laboratory activities, supporting students as appropriate to empower them to engage in line with course expectations	• Structured activities to help students learn about elaborate environment (Spagnoli *et al.*, 2017) • Bridging courses to connect prior learning to new learning (Spencer-Briggs and Rourke, 2023) • Emphasis on laboratory skills and techniques needed for competent laboratory work (Hensiek *et al.*, 2017; Seery *et al.*, 2017)
Ensure inclusion of all learners by presenting material in accessible ways to allow for text-to-speech, translation, and other student-led adaptations of materials	• Establish an accessible culture prioritising inclusion of all students and staff (Egambaram *et al.*, 2022) • Embedded accessibility in all documentation in line with principles of universal design for learning (Miller and Lang, 2016; D'Agostino, 2022) • Consideration of range of abilities and means of communication of students in laboratory settings (Pagano and Quinsland, 2007; D'Agostino, 2022)

good practice regarding accessibility of documentation such as the use of Word rather than PDF documents, and inclusion of close captions for video is beneficial to all learners.

Guiding Principle 2: ensure coherence with intended learning goals among the professional learning community for staff involved in teaching laboratory classes

Undergraduate laboratory work is often arranged with the whole class of students divided into smaller groups. A consequence of this is that for many laboratory courses, the community involved in teaching is larger than corresponding lecture courses – and likely includes a range of academic and technical staff and postgraduate student instructors. Many of the challenges associated with laboratory learning arise from mixed messages about the purpose of laboratory work, with different staff engaged in teaching laboratory classes having different goals, values, and expectations for their laboratory class (Boud *et al.*, 1986). Striving for consistency of learning experience should be a major goal for all involved in laboratory education, although there are challenges to achieving this in practice. The literature is replete with reports regarding faculty conceptions of learning goals (Connor *et al.*, 2023), categories of goals (Reid and Shah, 2007), and even advocacy of focussing on a single goal (Seery, 2020). In the absence of clarity, there is a misalignment between staff, teaching assistants, and students of what goals for laboratory work are (George-Williams *et al.*, 2018b). Within this spectrum of possibilities, establishing meaningful learning goals for the laboratory course intended is an important first step towards consistency among the laboratory teaching community.

As mentioned, in curriculum design the process of constructive alignment intends to establish coherence among (i) learning outcomes, (ii) learning and teaching approaches and (iii) assessment methods (Biggs, 2003). The potential scope of learning goals can be very varied. A recent review summarising learning outcomes in laboratory work reported in over 350 empirical studies provides a useful overview on potential outcomes that could be included (Agustian *et al.*, 2022a). Five distinctive clusters of learning outcomes were evident in previously published work: experimental skills; disciplinary learning; higher-order thinking skills; transversal competencies; and affective outcomes. Some of the reported components within these categories are shared in Table 2, highlighting the broad variety of *potential* learning outcomes that *may* be obtained from laboratory work. Clearly not all outcomes can be obtained in all laboratory classes, and with such variance, consideration is needed at curriculum design stage on what learning outcomes are appropriate for particular classes, class groups, and stages in the curriculum. Therefore there is typically a progression throughout the stages of study, and learning outcomes at each stage likely reflect this progression. This has led to curriculum models focussing on particular learning outcomes such as the development of practical skills through a curriculum (Campbell *et al.*, 2022), or considering the key components at different stages of the curriculum from introductory stage (Adams, 2020) through the curriculum to upper level and capstone undergraduate projects (Seery *et al.*, 2019b). While individual capstone undergraduate projects are required components of laboratory work in many education systems, they are outside the remit of these guidelines as they have a different format to typical large-scale undergraduate laboratory classes. Our *Guiding Principle 7* does however incorporate examples of implementation of course-based undergraduate research experiences which have been show to operate at scale (Watts and Rodriguez, 2023).

Much of the work on learning outcomes and curriculum design will be done well in advance of the laboratory course implementation, and the aim of their active consideration is to ensure all those involved in laboratory teaching are aware of what the intentions are. This is best achieved by building a supportive community, sharing teaching strategies and purposes (Connor and Raker, 2023). More general professional

Table 2 Learning outcomes reported in the literature clustered by type as identified by Agustian *et al.* (2022a; 2022b), with examples of some of the identified categories within each cluster – for full details see source

Learning outcome type	Example
Experimental skills	• *Practical skills & conducting experiments*: learning how to do a technique and complete an experiment • *Data analysis and interpretation*: learning how to analyse experimental data and draw conclusions in relation to the purpose of the experiment • *Designing experiments*: learning how to set up a process to find out the answer to a question
Disciplinary learning	• *Conceptual understanding and theory practice connection*: learning chemistry concepts as a result of laboratory activity (note that outcomes in this category have mixed findings in the literature – see Finne *et al.* (2023)) • *Academic achievement and mastery*: learning resulting in improved academic achievement, usually in cases where laboratory design had been reformed
Higher order thinking skills	• *Problem solving*: learning how to approach a problem, often in less-structured or research settings • *Argumentation*: learning how to construct a claim and provide evidence in support of that claim, usually in well-designed settings
Transversal competencies	• *Collaboration*: learning how to engage with others when engaging in the scientific process • *Communication (oral and written)*: learning how to communicate findings through a report, with higher levels of competencies reflected in more structured activities
Affective outcomes	• Communication of learning outcomes in a way that help students manage expectations, motivations, and reduce anxieties, promoting a positive professional identity associated with laboratory work

learning communities for chemistry laboratories have been described (Buntine *et al.*, 2007). In a departmental context, this kind of community is one that can help foster awareness and alignment through activities such as (Richards-Babb *et al.*, 2014; Flaherty *et al.*, 2017):

(i) facilitating those teaching and supporting students to complete the laboratory activities in advance of the teaching schedule;

(ii) co-creating documentation and support materials for laboratory teaching to ensure consistency in what is presented to students; and

(iii) providing specific development for faculty and teaching assistants in appropriate pedagogical methods for laboratory teaching, assessment, and feedback.

This work can be complemented to include best practices regarding accessible and equitable approaches in the teaching laboratory so as to pro-actively promote positive learning environments, and address inappropriate student practices such as gendered task distribution (Sarju and Jones, 2022).

These kinds of actions and discussions can help foster agreement among staff involved in teaching in laboratories about the learning outcomes and their place in the curriculum, in their specific context. Unlike the determination of learning outcomes, this context-specific work is ongoing, as there is often a turnover of teachers for each course, including student instructors. Thus, for each new iteration of a course, there is an important task of engaging with all of those involved in teaching. This can begin with the course meetings with those involved in teaching prior to the course start. Very recent work has explored in depth how graduate teaching assistants manage their classroom environments, and identified the kinds of observations of student behaviours that are made and what is inferred from them. This work shares a highly valuable guidance for developing graduate teaching assistants' capacity to lead in their laboratory teaching work (Geragosian *et al.*, 2023).

The course leadership may also help new teachers by supplying written teacher guidelines for specific laboratory activities, and by organizing the exercises so experienced and new teachers are present in the laboratory at the same time, or that new teachers have an experienced teacher to consult. It is well documented that students value high consistency in regards to organisation and management of their curriculum (Burgess *et al.*, 2018), and hence these approaches, alongside student-facing materials should be designed with consistency in mind. This leads to the alignment of guidelines regarding expectations, assessment and feedback protocols, and supporting resources in each of the laboratory sections that they will engage with (Table 3).

Guiding Principle 3: incorporate pre-laboratory activities so that students can prepare for learning in a complex environment

It is well established that facilitating students' preparation for laboratory work has a range of benefits for learning. These include benefits relating to experimental competencies, such as improved accuracy and efficiency of laboratory work as well as capacity to focus attention on more complex techniques; conceptual understanding, such as higher levels of discussion relating to laboratory concepts leading to feelings of greater autonomy in laboratory work; and affective dimensions, with pre-laboratory activities helping students feeling more confident, less anxious, and having higher motivation to complete practical work (Agustian and Seery, 2017).

Laboratory learning environments are known to impose a high cognitive load on learners (Johnstone and Wham, 1982; Winberg and Berg, 2007), and thus activities that tend to reduce some of that load by presenting key information in advance – often when it had not yet been covered in a complementary lecture syllabus. For example an analytical lecture and laboratory course where the materials could not be easily synchronised was supported by incorporating a pre-laboratory lecture, an experimental video, and a data analysis video, all aimed at supporting leaners at the different stages of laboratory work in the context where students may not have had corresponding lectures (Schmidt-McCormack *et al.*, 2017). Design principles to inform the content of preparation activities were outlined by Agustian and Seery (2017), who distinguished between *supportive information* that should be included in preparation materials – information about the overarching concepts relating to an experiment, or why a given protocol was appropriate – and *procedural information* that can be given as needed within the laboratory environment itself, such as specific aspects about completing experimental technique. That work intended to prompt educators to think about what it is their pre-laboratory work is for, and therefore what it should ask students to do.

A variety of examples from recent literature illustrate how these intentions can operate in practice. In their work for

Table 3 Actions to take to align with *Guiding Principle 2* and associated exemplary practices from the literature

Action	Example
Define and share module and laboratory specific outcomes so that appropriate teaching and learning methods and assessment can be implemented	• Source potential laboratory learning outcomes and define those appropriate for stage of study (Agustian *et al.*, 2022a) • Define intended curriculum goals appropriate for stage and/or overall intended outcomes (Seery *et al.*, 2019b; Campbell *et al.*, 2022)
Develop a departmental culture and module community for those involved in teaching laboratory work, with formalised continuing professional development, mentoring, and sharing to build coherence and share best practices	• Plan departmental and laboratory course communities based on the discussion and practice of laboratory activities, including mentoring and ongoing continuing professional development (Connor and Raker, 2023) • Ensure the transient community of teaching assistants have appropriate upskilling to engage fully in their teaching activities (Flaherty *et al.*, 2017; Richards-Babb *et al.*, 2014; Geragosian *et al.*, 2023)

organic chemistry laboratory work, Gorman *et al.* (2021) used this framework to guide the preparation of students for the techniques that they would need to complete by prompting students to read the procedure in advance, watch associated technique videos, and answer questions based on these techniques. Rodriguez and Towns (2018) tasked students in advance of their general chemistry laboratory work to write pre-laboratory questions that focussed on connecting between the conceptual content, the purpose of the experiment, and the related method, aligning this approach with the scientific practices of planning and carrying out investigations. Seery *et al.* (2019a; 2019b; 2019c) described similar intentions for advanced physical chemistry laboratories, advocating preparative materials that would enable students to learn why particular approaches were useful for the experimental goals, alongside the rationale for overall experimental considerations. Moozeh *et al.* (2019) describe their design of pre-laboratory animations and quizzes in organic chemistry that aimed to elaborate on theory, rationale for procedures, and on the purpose of the experiment in relation to students' overall learning goals. These examples illustrate how pre-laboratory activities can actively engage students and help scaffold students' understanding of what to focus on and how to engage in laboratory activities, rather than just providing general information in a passive way.

Pre-laboratory activities typically incorporate some kind of quiz or prompting questions, which enable students to check their understanding, as well as highlight the priorities of the intended laboratory work through what is exemplified in the questions asked (Rodriguez and Towns, 2018). Other approaches avoid direct quizzing of materials, and instead incorporate discussion at the beginning of laboratory classes that is based on preparation activities (Seery *et al.*, 2019a; 2019b; 2019c), or even discussion facilitated in online settings prior to class (Veiga *et al.*, 2019). All of these approaches had well-designed preparation activities built into curriculum delivery, which were aligned with the intended student activity in the laboratory, and the consequent assessment of laboratory work.

Pre-laboratory activities will help students set expectations for what is intended with laboratory work. Coherence of pre-laboratory activities with the intended learning goals (see *Guiding Principle 2*) help students align the priorities regarding the purpose of their attention, and relate this with other, often theoretical, aspects of their curriculum (Moozeh *et al.*, 2019). This last point requires explicit consideration; recent work such as that by Finne *et al.* (2021) have demonstrated that students have may a range of different conceptions of laboratory work and its purpose, as well as a variety of considerations about the integration of theory and practical work (Finne *et al.*, 2023). Preparation activities can help clarify these intended goals for students to enable them to engage in a meaningful way to align with these goals. Some general guidance drawn from across these approaches can be summarised for those considering developing their own preparation materials (Table 4).

Guiding Principle 4: design scenarios to promote dialogue

Teaching laboratories are inherently active learning environments, with staff:student ratios that are conducive for dialogue and extended engagement with students. This is highly valued by students and staff (Jørgensen *et al.*, 2023), with the time and opportunity to directly interact with teachers in the laboratory setting playing an important role for the scaffolding of students' learning through dialogue and feedback (Finne *et al.*, 2022). However, available laboratory time will often be busy with activities, leaving students little time to reflect on what they are doing and what they are finding out. Conversely, time that could have been used on dialogue and reflection is seen as being wasted (Finne *et al.*, 2021). The intended learning outcomes will likely not be achieved if the students are just "doing things" in the laboratory without conceptualizing them. Students have to reflect on what they do with peers and instructors, as they do it; or what has been described elsewhere as reflection-in-action (Schön, 1983).

Table 4 Actions to take to align with Guiding Principle 3 and associated exemplary practices from the literature

Action	Example
Decide on format and design of pre-laboratory activities ensuring their alignment with learning goals and assessment intentions	• Screencast videos with combination of notes slides and laboratory activities highlighting conceptual and practical information needed in advance of laboratory work (Schmidt-McCormack *et al.*, 2017) • Information describing concepts necessary in advance of practical work along with some context to give real world context and broader utility value to increase motivation and engagement (Moozeh *et al.*, 2019) • Prompts to read laboratory manual and associated technique videos which highlighted existing and new skills associated with the experiment (Gorman *et al.*, 2021)
Incorporate mechanisms to check intended learning	• Quizzes to be completed in advance of practical work emphasise connection between content, purpose, and method/approach (Rodriguez and Towns, 2018) • Discussion prompts facilitate dialogue between teaching assistants and students at the beginning of class that builds on preparation activity (Seery *et al.*, 2019a; 2019b; 2019c) • Pre-laboratory discussion forum where students could contribute to and view discussions about preparing for laboratory work (Veiga *et al.*, 2019)

This special learning environment provides opportunities to create spaces where students can engage in the process and practices of learning how *to do* chemistry (Seery, 2020); experiences that are known to enhance learning (Russell and Weaver, 2011). However, the mere setting of a laboratory environment does not automatically lead to meaningful activity, and in the absence of well-designed learning scenarios, students may focus on completing the tasks at hand as efficiently as possible, to focus on post-laboratory work and its corresponding assessment (DeKorver and Towns, 2015; DeKorver and Towns, 2016).

Consideration is needed then not just for the experiment that is at the heart of a laboratory activity, but additionally for the design of learning scenarios intended in the session. Alongside supporting resources mentioned above, the primary means of scaffolding activities students undertake in the laboratory is the laboratory manual, so its design needs careful consideration. Laboratory manual instructions have been considered with regards to their design of how information is presented so as to leave cognitive capacity for students to engage more actively in laboratory tasks (Dechsri *et al.*, 1997; Mundy and Potgieter, 2020). Laboratory manuals and other guidance should incorporate prompts for activity in the laboratory: decision making, discussion with peers, with teaching assistants, and where the laboratory activity calls for it, in plenary sessions. These can range from formal to informal dialogue settings, but are purposefully designed into the laboratory experience. Examples of these in action follow, with a summary presented in Table 5.

Highly formalised aspects of structuring dialogue around activity include instances whereby students are tasked with agreeing on a common purpose or experimental approach to take in their laboratory work (Varadarajan and Ladage, 2022). In these instances, the focus of laboratory dialogue shifts discussion away from simply managing and completing laboratory work (Tapper, 1999), or trivial aspects of discussing procedure or using instrumentation, and instead shifts towards discussion on planning, analysis, and meaning-making (Xu and Talanquer, 2013). Similar observations are found in argument-driven inquiry laboratories, whereby student dialogue is structured around identifying tasks to address a problem, developing and implementing a method to gather appropriate data, production and subsequent presentation of an argument addressing the answer to a problem grounded in the available data. Each of these dialogue structures are embedded at various points in the laboratory activity, structuring the entire experimental exercise around dialogue and co-creation (Walker and Sampson, 2013).

Dialogue can also be incorporated into laboratory activity in less formal ways. Mistry *et al.* (2016) describe tasking students in advance of laboratory work to devise a procedure for a particular stage of an experiment (work up from an organic reaction), with students having to present their case for discussion with teaching assistants at the beginning of laboratory time. Initiating decision-making in advance of laboratory work means it leaves the potential for timely review, and so better aligns with health and safety concerns that may make planning in the moment more challenging. Spagnoli *et al.* (2019) shared a useful initiative involving students choosing approaches that they could take in the planning stages, which provide for useful discussion prompts in the laboratory class itself. McGarvey (2020) described a data-pooling activity whereby all students in the laboratory contribute their results to a shared area (such as a whiteboard or online sharing space), facilitating a plenary dialogue and a more meaningful discussion around issues such as experimental error and theory-experiment relation. Seery described the incorporation of a number of discussion prompts in laboratory protocols with the expressed purpose of prompting and normalising dialogue in and about laboratory work. These included dialogue prompts at the start of the laboratory based on pre-laboratory preparation, prompts in preparation for planning stages in laboratory work, prompts for review of draft data, and prompts for salient points to discuss in the laboratory assessment (Seery *et al.*, 2019a; 2019b; 2019c). Including such discussion prompts in the schedule along with details of what to discuss will also help new teachers focus on the most relevant goals (see *Guiding Principle 2*).

The above examples all have in common the meaningful incorporation of dialogue into laboratory classes, and it is clear that such activities take time. The benefit is that activities that structure a higher level of dialogue result in a more meaningful learning experience for students, with opportunities for formative feedback being embedded into the formal structures of the laboratory activities. This realises the laboratory as a

Table 5 Actions to take to align with Guiding Principle 4 and associated exemplary practices from the literature

Action	Example
Plan laboratory activities and learning materials to leave sufficient time for meaningful dialogue about laboratory work	• Students value time in the laboratory for discussion and perceive this to be more valuable than written feedback (Jørgensen *et al.*, 2023)
Establish core principles of embedding dialogue into laboratory teaching through the design of activities involving dialogue forms	• Design laboratory activities so that students engage in meaningful dialogue about their results, for example through data pooling (McGarvey, 2020) • Setting out dialogue prompts and suggesting what can be covered in those prompts will help formalise dialogue interactions in the laboratory (Seery *et al.*, 2019a; 2019b; 2019c; Varadarajan and Ladage, 2022)
Extend dialogue forms into feedback, by making clear to instructors and students the different forms of feedback available and how it can be followed up	• Incorporate formal feedback engagement points into laboratory work so that students meaningfully use it in subsequent activity (Katja and Olga, 2015)

productive, active space where student learning is supported through dialogue and feedback around the process of doing science (Jørgensen *et al.*, 2023).

Dialogue also extends into the feedback that we share with students in assessment. Assessment and feedback are discussed more fully later (*Guiding Principles 8* and *9*) but it is useful to consider dialogue forms that may be used as suggestions for kinds of dialogue that may occur in the laboratory. These include "corrective" comments, which aim to correct a mistake directly, "directive", which aim to promote awareness of the way that things should be done, and "epistemic", which aim to prompt thought about additional or related actions (Kirschner and Neelen, 2018). Discussion and sharing of these conversation types among the laboratory teaching community will help to ensure consistency and share good practice. These informal feedback protocols *in* the laboratory can be fostered through a discursive and dialogic approach (Agustian, 2022), which refers to feedback on what students are doing in the laboratory by eliciting their reasoning and chemical thinking.

Guiding Principle 5: include tangible opportunities for students to learn about safe and sustainable practices

Because of the mostly routine nature of scheduling laboratory work, many of the considerations relating to safety and sustainability associated with laboratory teaching are pre-determined well in advance of actual teaching. These considerations are part of the professional practice regarding laboratory work, but students may not be aware of them as they are often implicit in implementation. For example, decisions regarding choice and amount of chemicals to use are typically made in the planning phase, in advance of students' participation. Many of these decisions could afford the opportunity to model professional activities that relate to safe and sustainable practices if they were made explicit. Where feasible, involving students more proactively in these decisions means they can observe and model how professional decisions are made in this context. This relates to factors that are important for building a safety-conscious culture; (i) administrative commitment safety – the infrastructure and supports in place to promote a safety culture; (ii) safety leadership – the explicit and implicit messages from those in teaching scenarios about the importance of safety; (iii) laboratory hazard recognition – identifying hazards involved in teaching laboratories; and (iv) laboratory safety practices – how appropriate safety procedures are practiced in the laboratory (Marin *et al.*, 2019). As has been said for laboratory teaching as a whole, it is likely that a safety-conscious culture will be productive when all those involved in the teaching context share a common message and perspective.

Promoting a safety-conscious culture therefore involves a combination of approaches (Table 6), from demonstrating and emphasising the importance of safety considerations in curriculum structure and learning materials, through to engaging students directly in the considerations about the identification of hazards and the lowering of associated risks. The most convenient means of engaging students in safety considerations is to involve them as part of their overall experience. A substantial suite of resources aligned to the incorporation of hazard identification and minimisation has been shared through the American Chemical Society Center for Lab Safety (2023), alongside a complementary framework for inclusion of associated activities in undergraduate teaching (Bocwinski *et al.*, 2021; Finster, 2021). Other available materials include various hazardous scenarios (Gaynor, 2021) and quizzes for students to check their understanding of safety issues prior to laboratory work (Loughlin and Cresswell, 2021). These preparatory activities can be continued in the laboratory session itself, such as a focus on the handling and disposal of laboratory materials (Walters *et al.*, 2017). In terms of overall curriculum design, these approaches will scaffold students' approaches in preparation for any future independent laboratory work.

An increasingly important consideration regarding professional identity is the growth in importance of sustainability: 90% of respondents to a large survey (n = 670) from the Royal Society of Chemistry who were working in chemistry sciences research laboratories agreed that it is important to consider sustainability in their day-to-day work (Royal Society of Chemistry, 2022). Broader issues relating to sustainability can be introduced either in the laboratory activities or as associated discussion exercises. For example, substantial work on microwave chemistry as alternatives to traditional synthesis approaches is a useful platform for students to consider energy demands of industrial synthesis or as a prompt for considering the sustainability of raw materials involved in the laboratory activities (Diekemper *et al.*, 2019). Emerging work in systems thinking (Reynders *et al.*, 2023) provides curriculum approaches for connecting source of materials being used in the context of overall sustainability (Murphy *et al.*, 2019; Paschalidou *et al.*, 2022). The intention is that discussion about

Table 6 Actions to take to align with Guiding Principle 5 and associated exemplary practices from the literature

Action	Example
Promote a culture of safety by ensuring consistency in message across all dimensions of laboratory work, empowering students to take knowledgeable actions in relation to safety	• Formalise a framework for embedding safety culture and considerations into curriculum design and delivery (Finster, 2021) • Sharing of resources and messaging emphasising strong safety culture giving students agency about their safety (Walters *et al.*, 2017; Marin *et al.*, 2019; Gaynor, 2021; Loughlin and Cresswell, 2021)
Incorporate opportunities to discuss sustainability in relation to the conduct of laboratory work, through options of alternative approaches or in consideration material use and source	• Laboratory activities that consider sustainability in a meaningful way (Diekemper *et al.*, 2019; Paschalidou *et al.*, 2022)

how to move towards more sustainable laboratory practices should not be implicit, but rather needs to be made visible to and discussed with students.

Guiding Principle 6: model modern scientific work practices through facilitation of group and interdisciplinary work

To further the development of understanding scientific processes and practices described in previous guiding principles, it is valuable to raise awareness about the extent to which scientific advancements are grounded in work done by large and often multi-disciplinary teams (Fortunato *et al.*, 2018). The average number of authors on research papers increased from 1.9 in 1955 to 3.5 in 2000 (Wuchty *et al.*, 2007). At the undergraduate stage, group and team dynamics can be developed by activities that demonstrate how individual contributions align with overall team goals. This is a challenging task, as it may differ substantially from the predominant experience of viewing learning as a matter of individual acquisition. Furthermore, students' prior experiences may involve only completing a well-defined laboratory task in isolation or in pairs. It also adds challenges to the teaching scenario when facilitating productive groupwork, and useful guidance on rubrics for assessing and thus facilitating group work, including aspects such interpersonal communication (Reynders *et al.*, 2019).

A common approach to introduce collaboration through teamwork is by facilitating variance in experimental procedures such as reagents or conditions, so as to generate a larger dataset for analysis. Encouraging students to be aware of variance in methods and results has a potential for developing a critical mindset regarding experimental data (Agustian *et al.*, 2022b). Examples from the literature include experiments in organic synthesis (Santos Santos *et al.*, 2010) and spectroscopy (Marincean *et al.*, 2012), demonstrating the utility of this approach in more challenging laboratory contexts. MacKay and Wetzel (2014) provide extensive detail on this approach in an experiment where different students in the cohort are tasked with exploring different aspects that may affect the Wittig reaction, with students required to make a hypothesis about their choice of reagent (from an approved list) and conduct an experiment to test that hypothesis. Data compilation and sharing in an online space at the end of the experiment facilitates further refining of hypotheses and analysis as students prepare their final reports. As well as varying parameters within an individual experiment, other work has explored how differing team contributions in a laboratory setting can contribute to a shared understanding. An innovative analytical chemistry laboratory course tasked different groups of students with quantitative analysis, but with each team given one of an array of experimental techniques (Schwarz *et al.*, 2020). As a plenary, students were tasked to present their poster in clusters (with each cluster being a combination of all available techniques).

More complex interdisciplinary work involving interaction outside of the teaching context is more challenging to coordinate. However, there are instances where this can be achieved simply, such as where compounds prepared by students in an organic laboratory are used as starting materials for students in another laboratory (Kasting *et al.*, 2015). More tangible interdisciplinary activities – where students interact with topics outside their discipline – are typically reserved for more advanced specialist or research work. Some valuable reports are available as exemplars, such as the synthesis and subsequent biological activity of nanoparticles (Scott *et al.*, 2023), or synthesis and DNA-binding capacity of ruthenium complexes (Rabago Smith *et al.*, 2012).

While dialogue scenarios (*Guiding Principle 4*) are a good way to structure this discussion, this work often extends into post-laboratory work and the consequent laboratory report that students are usually tasked to prepare. Guidance for students on how they can engage in this data sharing and discussion has been elaborated on by McGarvey (2020). This kind of approach offers valuable opportunities for discussion of broader ethical issues relating to recording and representing results obtained in the laboratory. This is an issue that has gained substantial attention in recent years with several high-profile cases of false or misrepresented data, suggesting a need for more pro-active consideration in our curricula. Early work in undergraduate laboratories could focus on appropriate means to handle data and discuss errant results (Johansen and Christiansen, 2020) (Table 7).

Guiding Principle 7: embed opportunities for creativity and open experimentation

Bretz's work on meaningful learning in the laboratory points to the importance of students making a conscious choice to build connections between prior knowledge and their new learning materials (Bretz *et al.*, 2013). Such a choice will be influenced by interest and engagement. Students attending university place

Table 7 Actions to take to align with Guiding Principle 6 and associated exemplary practices from the literature

Action	Example
Encourage students to think about collaborative approaches to doing science though the design of activities whereby each student contributes a component of the overall result	• A range of collaborative approaches are possible, through sharing out different experimental protocols (MacKay and Wetzel, 2014; Kasting *et al.*, 2015) • Tasking students with a range of complementary activities to contribute to a whole result (Schwarz *et al.*, 2020) • Introducing inter-disciplinarity with different disciplines contributing to an overall conclusion (Rabago Smith *et al.*, 2012; Scott *et al.*, 2023)
Structure student work in the processing and interpretation of data in their post-laboratory activities, including guidance on good practice and ethical considerations in relation to data handling	• Data pooling activities can open up conversations about data, experimental error, and how to handle variable results in a way that is meaningful to students (Johansen and Christiansen, 2020; McGarvey, 2020)

high emphasis on joining laboratory courses and have high expectations of how they will differ from their prior learning, but are often *under*whelmed by the laboratory work they experience, and increasingly so as they move through their programme of study (George-Williams *et al.*, 2019b). Even for students who are choosing to specialise in chemistry, their main intention when undertaking laboratory work in traditional settings is to complete the laboratory work as efficiently as possible (DeKorver and Towns, 2016). This observation will not surprise those who teach in laboratories, and it is one that has led to a long legacy of efforts to increase interest and motivation in laboratory learning, such as seeking to connect content with real world context and/or by introducing meaningful "experimentation" by situating laboratory work in the context of particular problems to be addressed (some examples include Kelly and Finlayson, 2007; McDonnell *et al.*, 2007; Flynn and Biggs, 2012; Shultz and Li, 2016; Dood *et al.*, 2018; George-Williams *et al.*, 2018a; Hamper and Meisel, 2020; Varadarajan and Ladage, 2022).

Perhaps the easiest means of introducing interest and allowing for creativity is to situate the laboratory in a real world context (Ziebell *et al.*, 2019). George-Williams *et al.* (2020) describe an impressive array of laboratory experiments set in professional and real-world contexts designed with industry partners. Their work demonstrated that alongside general enjoyment and engagement with context-based laboratories, the specific focus on industry-relevant materials and 'workforce context' was appreciated by students, as they were learning chemistry that was relevant to society. This was especially highlighted in the contrast the same students reported about their experience of and engagement with traditional laboratory approaches.

Situating laboratory work in real world contexts allows for some trial and error, making decisions, and other aspects of "doing science" that come under an umbrella term of open experimentation. It is clear that while safety and organisational pragmatism will limit what students can do, there are many examples of empowering students to design and lead their own experimental approaches within guided frameworks. Such an approach means that the associated assessment needs to shift from getting "the right answer" to how students conduct the task – from product to process – as well as time for students to try out things and reconsider approaches based on experimental observations. Deciding on the extent to which to allow for open-ended approaches needs some care. Substantial work under the umbrella of inquiry based learning has led to the characterisation of different levels of inquiry (Fay *et al.*, 2007; Bruck *et al.*, 2008; Xu and Talanquer, 2013, see rubric included in Supplemental Information to cited article) with levels categorised using terms such as verification, structured, guided, and open. These provide useful templates for thinking about which aspects of the laboratory work to provide guidance for, and which aspects are given to students to decide on. In moving from verification to structured, for example, learners' specific instructions on what procedure to follow may be replaced by the prompt on what data is to be gathered, along with general procedural guidance that omits specific instructions. Care is needed to appropriately structure increasing extents of openness and this often needs to be built in to curriculum design approaches, so that the overall engagement is supported (George-Williams *et al.*, 2020). Students may be capable of identifying individual components of work in an overall experiment, but less so at drawing those concepts together without prior experience (Scoggin and Smith, 2023), so curriculum design approaches need to consider how to build students' capacity in these decision-making processes. This can be done by getting students to discuss their choices prior to actual work (Mistry *et al.*, 2016; Varadarajan and Ladage, 2022) or allowing students gain familiarity in approaches before embarking on using it in a more open-ended way (Seery *et al.*, 2019a; 2019b; 2019c; Thomson and Lamie, 2022).

Alongside capstone-research projects in the final year, course based undergraduate research experiences in other years allow further opportunity to include inquiry and creativity. A recent overview on the implementation of CUREs including those with large enrolment classes advocates some core principles that can be embedded in these research experiences; namely building from hypothesis development, providing time in the laboratory to develop the necessary skills and engage in experimentation, and allowing for evaluation of data in light of the hypothesis under consideration (Watts and Rodriguez, 2023). Such activities have been shown to foster increased interest, engagement, and persistence of study in other disciplines (Jordan *et al.*, 2014; Hanauer *et al.*, 2017) (Table 8).

Table 8 Actions to take to align with Guiding Principle 7 and associated exemplary practices from the literature

Action	Example
Incorporate opportunities for students to engage with laboratory content creatively through the use of real-world contexts	• Laboratories situated in societal or industrial context enthused and motivated students and offered scope for creative engagement (Dood *et al.*, 2018; George-Williams *et al.*, 2018a; George-Williams *et al.*, 2020) • Course based undergraduate research experiences allow time and space for hypothesis development, skills work and experimentation, and evaluation and analysis of data (Watts and Rodriguez, 2023)
Determine opportunities to build in open experimentation for students that are structured so that they can engage in a meaningful way	• Determine the extent of 'level' of openness and how current laboratory work could be adopted (Xu and Talanquer, 2013) • Ensure students are supported by considering the various aspects of what is new to them in a given scenario (Scoggin and Smith, 2023) • Build in activities to help students gain confidence or capability in more open-ended approaches (Mistry *et al.*, 2016; Seery *et al.*, 2019a; 2019b; 2019c; Thomson and Lamie, 2022)

Guiding Principle 8: implement a variety of assessment types to align with intended learning goals

As indicated above in *Guiding Principle 2*, learning outcomes for laboratory work cover a broad variety of competencies, skills, and attributes. Traditional assessment approaches usually rely on students' written work, which, while appropriate for considering students' understanding of the overview and analysis of experimental work, is insufficient for assessment of experimental skills, engagement in scientific practices, or transversal skills beyond the written form (Prades and Espinar, 2010). This insufficiency has led to a broad variety of assessment types being introduced at scale into undergraduate laboratories. However, there is a scope for developing assessment approaches that consider the multifaceted aspects of learning in the laboratory, through more integrated and comprehensive methods (Agustian, 2022). Some exemplar approaches are provided below, aligned with the clusters of learning outcomes described in *Guiding Principle 2* (summarised in Table 2).

There are now well-established protocols for assessment of laboratory skills in widespread use. Towns has pioneered the approach involving student demonstration of a skill while being videoed, and submission of the video as an artefact for assessment, most easily corrected using a rubric interface (Towns *et al.*, 2015; Hensiek *et al.*, 2017). Variations of this theme include incorporating aspects of formative and peer assessment (Seery *et al.*, 2017) and formative and self-assessment (Taylor *et al.*, 2009; Lau, 2020). All approaches invoke student reflection on their capacity to perform a skill based on their evidence captured on video. Video assessment allows for students to demonstrate their capacity to achieve the task, as well as explain what they are doing, and why they are doing it. The latter point is very valuable when experimental tasks move beyond the introductory level, providing a means for students to explain the basis to the experimental approach (for example, how instrumentation works) as they are demonstrating it (Seery *et al.*, 2019a), invoking the pedagogic benefits of student generated video (Gallardo-Williams *et al.*, 2020). As well as being a means of assessment, the use of these approaches repeatedly results in significant improvement in laboratory skills (Jacobsen, 2023), that is to say the assessment is *for* learning, not just *of* learning. Other novel approaches on this theme include asking students to identify mistakes in a technique in videos provided (Accettone *et al.*, 2023). Rubrics have also been used to assess critical thinking and information processing skills in various chemistry laboratory settings, with reported benefits of both providing a means to assess broader outcomes relating to critical thinking, as well as facilitating student awareness of the assessment regime to the extent that they can self-grade and reflect on own progress (Reynders *et al.*, 2020).

Assessment of skills within laboratory environments have been managed in other ways. Hancock and Hollamby (2020) have shared a detailed overview of their assessment of a range of practical techniques through a "station-based practical exam" for significant (50–200) sized cohorts, in approaches similar to the objective structured clinical examination (OSCE) style assessment described for pharmacy students studying chemistry (Kirton *et al.*, 2014). Recently, assessment of advanced organic chemistry techniques by this approach was also described (Montgomery and Goll, 2023), along with description of rubric designs to help students engage meaningfully with feedback (Veale *et al.*, 2020). More generally, assessment of laboratory competencies in the broader sense have been described, with criterion explicitly aligned with learning outcomes made visible to students, with the task set to demonstrate capability in each of the competencies listed (Pullen *et al.*, 2018). Similar approaches to specification grading in organic chemistry on a very large scale (>1000 students) have recently been shared (McKnelly *et al.*, 2023). Approaches to encourage marking consistency across diverse cohorts by using template marking approaches proved beneficial and reduced time on marking (George-Williams *et al.*, 2019a).

Of course writing reports will remain a core and important aspect of summarising experimental work, and criticisms of laboratory reports as an assessment method tend to focus on their overuse. Like all new activities, report writing should be structured through curriculum implementation, and this is typically done by progressing from guided worksheets into full reports. Innovative approaches to helping structure students' approaches in learning how to write reports includes assessing different components of a report at different stages of the semester, and once the various components have been assessed and discussed, tasking students with writing a complete report (Deiner *et al.*, 2012; Capel *et al.*, 2019). These kinds of approaches naturally lead into supporting students for larger pieces of writing that they may engage in during undergraduate research activities (Seery *et al.*, 2019b). Bertram has demonstrated the importance and value of engaging students in assessment processes in the context of more open-ended project activity (Bertram and Tomas, 2023).

Finally, assessment of students as they engage in the "doing" of scientific processes is challenging. Innovative use of shared online documents can help manage the assessment of collaborative work including documentation of group experimental notes, conversations and forums; thus capturing a richer oversight of the students' engagement with their practical work (Lawrie *et al.*, 2016). Digital laboratory notebooks are becoming increasingly routine, and allow for student work to be documented digitally, enabling a wider variety of media to be more easily collated, reflecting the specialist nature of the laboratory context (Van Dyke and Smith-Carpenter, 2017; Bromfield Lee, 2018; Bravenec and Ward, 2023). Similar richness is observed in oral assessment, offering students more variety in how they present their work (Widanski *et al.*, 2020) and in how they can augment their written work with an associated oral component (Crawford and Kloepper, 2019) (Table 9).

Guiding Principle 9: establish common formal and informal feedback protocols and opportunity for students to use feedback to inform future approaches

Laboratory work provides substantial opportunity for ongoing feedback for students at regular intervals throughout the semester. As described in some of the above principles, there

Table 9 Actions to take to align with Guiding Principle 8 and associated exemplary practices from the literature

Action	Example
Align assessment approaches to the intended learning outcomes of laboratory work, including appropriate assessment of laboratory skills, and clarify those approaches with students	• Including assessment of laboratory skills where appropriate (Hensiek *et al.*, 2017; Seery *et al.*, 2017; Hancock and Hollamby, 2020) • Shared rubrics (Veale *et al.*, 2020) as well as specification grading (Pullen *et al.*, 2018; McKnelly *et al.*, 2023) and engaging students in consideration of assessment processes (Bertram and Tomas, 2023) can all help in clarifying and aligning assessment processes • Rubrics for critical thinking skills shared with students can help foster awareness of what is assessed in this aspect of laboratory work (Reynders *et al.*, 2020) • Include opportunities for self-and peer assessment (Taylor *et al.*, 2009; Lau, 2020) to help make assessment approaches tangible
Structure students' work in building capacity to write laboratory reports, including where intended the production of research project reports	• Include activities to help students learn and be assessed on particular aspects of laboratory work (Deiner *et al.*, 2012; Capel *et al.*, 2019) • Support assessment of the broader generation and contribution to group-produced work through, for example, the use of a wiki (Lawrie *et al.*, 2016)

are opportunities for formative feedback in pre-laboratory and in-laboratory settings, although much of what is perceived as feedback by students will be that on their final report or other output on the laboratory activity. Given the predominance of the laboratory report in chemistry assessment, there is surprisingly little literature on approaches to feedback in this domain, or how students use that feedback. However, there is an extensive general literature on feedback practices that can be drawn from to advocate good practice.

Assessment for learning (that is to say, formative assessment) and of learning (summative assessment) have important roles to play in education, and the two are often combined in laboratory teaching. A common example is when students deliver laboratory reports which are provided both with formative feedback in the form of comments intended to help student learning and future actions, and a grade (or a pass/fail). However, combining the two forms of assessment is this way is not unproblematic. While formative assessment directs students towards future actions, summative assessment is oriented towards assessing the students' current work, or past performance. When combined, students may choose to ignore the feedback if they passed, or focus quite narrowly on what it will take for them to pass if they failed. Indeed, recent research highlighted that teachers suspected that (some) students would disregard the comments, and that some of the interviewed students confirmed that they had not followed up on the feedback provided (Jørgensen *et al.*, 2023). Thus, students may focus on the summative assessment and disregard the formative assessment, which by intent is the more important for their learning.

A key question to consider, therefore, is how the formative and summative aspects are related in assessment practices on written work, and if there is a way of 'disentangling' the two (Harlen and James, 1997) to ensure that students will have an incentive to use the formative feedback provided. There are many ways in which this can be done. If students can resubmit their reports based on the comments they have received, that will ensure at least that the comments provided by instructors are being used. Seery suggested a means by which feedback on draft work can be provided verbally, so as to give students actions to take on board in producing their final report (Seery *et al.*, 2019a; 2019b; 2019c). Another option is that students provide formative peer-feedback to each other based on the feedback criteria prior to the summative assessment by the instructors (Basso, 2020). Encouragement to engage with feedback can also be prompted by tasking students with demonstrating how they have used the feedback provided on the previous report in the next ones in a log sheet. Indeed, formats where summative assessment is based on student work accumulated over time should be aimed at, in order to establish a valuable relationship between the formative and summative components of assessment (Dolin *et al.*, 2018).

Both formative and summative assessment should be based on explicit criteria, but formative assessment is also referenced towards the specific needs of the student (Dolin *et al.*, 2018). Thus, beyond separating the two aspects of assessment, an important step in developing good assessment practices is to develop relevant and explicit assessment criteria for written work that can be used for both formative and summative purposes. These assessment criteria should be closely related to the intended learning goals of the laboratory course. Clear and explicit assessment criteria will benefit both students and new teachers in the course, and will allow students to engage in self- or peer-assessment of their work, through the use of rubrics or other prompts for self-assessment (Reynders *et al.*, 2019; Reynders *et al.*, 2020). For instance, self-assessment methods include those that ask students to evaluate their reports using a rubric, with detailed components on various sections of the report (introduction, results, figures, *etc*) as well as overall report structure and format (Lim, 2009; Lim, 2015), or self-assessment of skills using a checklist for video review (Lau, 2020). Peer-feedback can be facilitated by tasking students to act as 'buddies', to check on each others' work (Musgrove, 2023). The intention of self-assessment rubrics are a means to allow students interact with the assessment criteria, so that they can make more meaningful relations between feedback and learning

Table 10 Actions to take to align with Guiding Principle 9 and associated exemplary practices from the literature

Action	Example
Share intentions with students for how formative and summative assessment will be incorporated into the module and ways for students to develop their understanding of feedback	• Discuss with students (and staff) intentions relating to feedback, and the role of formative feedback in the laboratory (Jørgensen *et al.*, 2023) • Opportunities for draft feedback (Basso, 2020), or for feedback given to be meaningfully incorporated into future work (Ellegaard *et al.*, 2018)
Consider ways to incorporate self- and peer-feedback	• Highly structured self- and peer- feedback activities for students to complete as part of their work (Lim, 2009; Lim, 2015; Lau, 2020; Musgrove, 2023; Bertram and Tomas, 2023) • Rubrics provide powerful means for students to engage in self-assessment (Reynders *et al.*, 2019; Reynders *et al.*, 2020)

outcomes. Bertram and Tomas (2023) extended this idea to incorporate evaluative judgements in a large project-based course, resulting in a series of feedback reflection stages in curriculum delivery, where students compared their self-assessment with instructor feedback, with action planning for future work incorporated as a means to help students take actionable steps for how they would approach their next activity, or future work. Approaches for prompting student engagement with formative feedback are summarised in Table 10.

Guiding Principle 10: provide a mechanism by which students can document and showcase their learning

Laboratory experiences are a core aspect of learning chemistry, but unlike taught aspects of the curriculum such as lectures, the experience of laboratory work is ephemeral. Lectures generate artefacts such as lecture notes and in more recent times, are video-recorded for review at later date. The experience of laboratory work – because of its specialised nature – remains in the laboratory. Laboratory reports are tangible artefacts generated as a result of laboratory work, but relate more to the documentation of completed work and subsequent analysis, rather than the activities completed within the laboratory itself. This raises the question then that while students are aware of the potential value of laboratory skills for post-graduation employment (Hill *et al.*, 2019; Hill *et al.*, 2022), there is less certainty on how students can showcase their laboratory experience in a meaningful way.

Assessment activities described in *Guiding Principle 8* involving direct assessment of laboratory skills provide one such mechanism. Many of these approaches involved awarding to students tangible certification – known as micro-credentials – realised in the form of digital badges. These aim to provide statements of achievement in specific techniques, acknowledging students' capacity to complete a technique to a defined standard. The intention is both to highlight to students their own portfolio of skills, and allow them to share it with others. If evidence such as video that led to the awarding of the digital badge is also in the public domain, students can showcase this directly as well, even in the absence of a digital badge (Seery, 2017).

Raising awareness among students themselves of their compilation of learning from a laboratory course likely needs plenary activities, so as to lift attention from the specific aspects of particular laboratory activities to the more general learning gained from a course. Reflection activities have been implemented that aim to prompt students into thinking about their thought processes as they worked in the laboratory, drawing together different forms of knowledge about the experiment and the procedure, as well as how they communicated their work, all in the context of the time available and engaging with others in the laboratory (Davidowitz and Rollnick, 2003). Such an approach aims to help students reflect on the bigger picture of their laboratory work to prompt thoughts of their own capabilities. Modifying reflection "exit interviews" such as those proposed by Crawford and Kloepper (2019) is another way to facilitate these activities. Other approaches to fostering reflection include an end-of-course critical reflection assignment, with students tasked to reflect on learning in a project laboratory, supported by detailed guidance prompts, including thinking about future directions (Burnham, 2020).

Similar structures to promote planning for future were incorporated in a project-based module by Bertram and Tomas (2023). Sharing detailed guidance provided to students, this work advocates working with students so that they can build on

Table 11 Actions to take to align with Guiding Principle 10 and associated exemplary practices from the literature

Action	Example
Include options for students to document their learning and skills in a manner that enables them to be showcased externally	• Offering students ability to record and share videos of them working in a professional environment (Seery *et al.*, 2017) • Sharing of explicit acknowledgement of skills (such as in the form of digital badges) help students express what skills and competencies they have gained as a result of laboratory work (Hill *et al.*, 2022)
Provide opportunity for reflection so that students can compile and outline their learning on their laboratory course	• Embedding assessment and other reflection activities for students to actively think about their progress in learning (Crawford and Kloepper, 2019; Burnham, 2020; Bertram and Tomas, 2023)

their feedback holistically, and plan future approaches, with prompting questions about recognising areas of strength from positive feedback, noting developmental comments, and thinking about actions to take in the future (Table 11).

Conclusions

These 10 guiding principles intend to help those involved in laboratory teaching explore ways in which they can consider their laboratory curriculum design and delivery, and a means to make appropriate changes to their laboratory courses or programmes. By aligning with Hounsell and Hounsell's congruence framework, we intend to consider the various aspects of laboratory curriculum design and delivery as they are enacted in practice. We share them at a time when many institutions and educators are looking at the post-COVID landscape which has prompted significant calls for reform. We intend these guiding principles to be a benchmark – a minimum set of expectations drawn from the past decade of research for considering laboratory teaching and learning environments.

Of course the nature of our disciplinary cultures means that many innovative approaches to teaching and learning in university laboratories have been published over the last decade. Substantial progress has been made, for example, in virtual reality settings for laboratory work (Dunnagan *et al.*, 2020; Gallardo-Williams and Dunnagan, 2022) with reports regarding their benefit to meaningful learning (Williams *et al.*, 2022). Mobile phone technology advancements (Moraes *et al.*, 2014; Koesdjojo *et al.*, 2015; Moraes *et al.*, 2015) and other low cost instrumentation (O'Donoghue and Fitzsimmons, 2022) have meant that students have easy access to a 'scientific instrument', allowing science to be carried out in a range of scenarios outside the lab. Augmented reality has demonstrated new and interesting ways in which contextual information can be shared as and when students engage in laboratory practices (Zhu *et al.*, 2018; Domínguez Alfaro *et al.*, 2022). Chemists – like all educators – are considering the impact of readily accessible artificial intelligence tools in their teaching and learning contexts, including the particular impact on laboratory education (West *et al.*, 2023). These latest tools offered by the forefront of technological advances are exciting (and daunting), but we believe it is feasible to consider them within the remit of our guidelines. Educators pondering the role of virtual reality, for example, may wish to think about the place of experimental craft in their learning outcomes (*Guiding Principle 2*), or whether these materials are valuable for enabling preparation (*Guiding Principle 3*). Augmented reality may be a prompt to consider formative feedback mechanisms – giving students feedback as they conduct a technique, for example (*Guiding Principle 9*). Artificial intelligence tools could be useful dialogue partners to consider results (*Guiding Principle 4*), or prompt reflection on suggested safety protocols (*Guiding Principle 5*). In other words, as with the early reports on video-taped media to help students prepare for laboratories in the 1970s (Simpson, 1973) or interactive simulations in the 1980s (Moore *et al.*, 1980), educators today can choose how these additional considerations and opportunities can affect their teaching and learning approaches, with those approaches guided by core principles. As our guidelines aim to influence what these core principles are, we hope that they will be of value and use to educators whatever their own particular context.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The work presented in this article was supported by the Novo Nordisk Foundation: Grant NNF 18SA0034990. MKS would like to dedicate this article to the memory of Professor T. Brian H. McMurry.

References

Accettone S. L. W., DeFrancesco C., King C. A. and Lariviere M. K., (2023), Laboratory Skills Assignments as a Teaching Tool to Develop Undergraduate Chemistry Students' Conceptual Understanding of Practical Laboratory Skills, *J. Chem. Educ.*, **100**(3), 1138–1148.

Adams C. J., (2020), A Constructively Aligned First-Year Laboratory Course, *J. Chem. Educ.*, **97**(7), 1863–1873.

Agustian H. Y., (2022), Considering the hexad of learning domains in the laboratory to address the overlooked aspects of chemistry education and fragmentary approach to assessment of student learning, *Chem. Educ. Res. Pract.*, **23**(3), 518–530.

Agustian H. Y. and Seery M. K., (2017), Reasserting the role of pre-laboratory activities in chemistry education: a proposed framework for their design, *Chem. Educ. Res. Pract.*, **18**, 518–532.

Agustian H. Y., Finne L. T., Jørgensen J. T., Pedersen M. I., Christiansen F. V., Gammelgaard B. and Nielsen J. A. (2022a) Learning outcomes of university chemistry teaching in laboratories: A systematic review of empirical literature, *Rev. Educ.*, **10**(2), e3360.

Agustian H. Y., Pedersen M. I., Finne L. T., Jørgensen J. T., Nielsen J. A. and Gammelgaard B. (2022b) Danish University Faculty Perspectives on Student Learning Outcomes in the Teaching Laboratories of a Pharmaceutical Sciences Education, *J. Chem. Educ.*, **99**(11), 3633–3643.

American Chemical Society Center for Lab Safety, (2023), *College Lab Safety Videos*, American Chemical Society, Available at: https://institute.acs.org/acs-center/lab-safety/education-training/safety-videos/college-lab-safety-videos.html (Accessed: November 2023).

Ausubel D. P., (1968), *Educational Psychology: A Cognitive View*, New York: Holt, Rinehart and Winston.

Basso A., (2020), Results of a Peer Review Activity in an Organic Chemistry Laboratory Course for Undergraduates, *J. Chem. Educ.*, **97**(11), 4073–4077.

Bertram A. and Tomas C., (2023), Evaluative judgement – a practitioner's case in chemistry research projects, *Chem. Educ. Res. Pract.*, **24**(1), 312–326.

Biggs J., (2003), *Teaching for quality learning at university*, 2nd edn, Buckingham: SRHE and Open University Press.

Bocwinski R., Finster D. C. and Weizman H., (2021), Framework for Teaching Safety Case Studies Using a Risk Management Approach, *J. Chem. Educ.*, **98**(12), 3824–3830.

Boud D., Dunn J. and Hegarty-Hazel E., (1986), *Teaching in laboratories*, Society for Research into Higher Education & NFER-Nelson Guildford, Surrey, UK.

Bravenec A. D. and Ward K. D., (2023), Interactive Python Notebooks for Physical Chemistry, *J. Chem. Educ.*, **100**(2), 933–940.

Bretz S. L., (2019), Evidence for the Importance of Laboratory Courses, *J. Chem. Educ.*, **96**(2), 193–195.

Bretz S. L., Fay M., Bruck L. B. and Towns M. H., (2013), What Faculty Interviews Reveal about Meaningful Learning in the Undergraduate Chemistry Laboratory, *J. Chem. Educ.*, **90**(3), 281–288.

Bromfield Lee D., (2018), Implementation and Student Perceptions on Google Docs as an Electronic Laboratory Notebook in Organic Chemistry, *J. Chem. Educ.*, **95**(7), 1102–1111.

Bruck L. B., Towns M. H. and Bretz S. L., (2008), Research and Teaching: Characterizing the Level of Inquiry in the Undergraduate Laboratory, *J. Coll. Sci. Teach.*, **38**(1), 52–58.

Buntine M. A., Read J. R., Barrie S. C., Bucat R. B., Crisp G. T., George A. V., Jamie I. M. and Kable S. H., (2007), Advancing Chemistry by Enhancing Learning in the Laboratory (ACELL): a model for providing professional and personal development and facilitating improved student laboratory learning outcomes, *Chem. Educ. Res. Pract.*, **8**(2), 232–254.

Burgess A., Senior C. and Moores E., (2018), A 10-year case study on the changing determinants of university student satisfaction in the UK, *PLoS One*, **13**(2), e0192976.

Burnham J. A. J., (2020), Skills for Success: Student-Focused, Chemistry-Based, Skills-Developing, Open-Ended Project Work, *J. Chem. Educ.*, **97**(2), 344–350.

Campbell C. D., Midson M. O., Mann P. E. B., Cahill S. T., Green N. J. B., Harris M. T., Hibble S. J., O'Sullivan S. K. E., To T., Rowlands L. J., Smallwood Z. M., Vallance C., Worrall A. F. and Stewart M. I., (2022), Developing a skills-based practical chemistry programme: an integrated, spiral curriculum approach, *Chem. Teach. Int.*, **4**(3), 243–257.

Capel N. J., Hancock L. M., Haxton K. J., Hollamby M. J., Jones R. H., Plana D. and McGarvey D. J., (2019), Developing scientific reporting skills of early undergraduate chemistry students, in Seery M. K. and McDonnell C. (ed.), *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton*, Dublin: Creathach Press, pp. 333–348.

Connor M. C. and Raker J. R., (2023), Measuring the Association of Departmental Climate around Teaching with Adoption of Evidence-Based Instructional Practices: A National Survey of Chemistry Faculty Members, *J. Chem. Educ.*, **100**(9), 3462–3476.

Connor M. C., Rocabado G. A. and Raker J. R., (2023), Revisiting faculty members' goals for the undergraduate chemistry laboratory, *Chem. Educ. Res. Pract.*, **24**(1), 217–233.

Crawford G. L. and Kloepper K. D., (2019), Exit Interviews: Laboratory Assessment Incorporating Written and Oral Communication, *J. Chem. Educ.*, **96**(5), 880–887.

D'Agostino A. T., (2022), Accessible Teaching and Learning in the Undergraduate Chemistry Course and Laboratory for Blind and Low-Vision Students, *J. Chem. Educ.*, **99**(1), 140–147.

Davidowitz B. and Rollnick M., (2003), Enabling Metacognition in the Laboratory: A Case Study of Four Second Year University Chemistry Students, *Res. Sci. Educ.*, **33**(1), 43–69.

Dechsri P., Jones L. L. and Heikkinen H. W., (1997), Effect of a labratory manual design incorporating visual information-processing aids on student learning and attitudes, *J. Res. Sci. Teach.*, **34**(9), 891–904.

Deiner L. J., Newsome D. and Samaroo D., (2012), Directed Self-Inquiry: A Scaffold for Teaching Laboratory Report Writing, *J. Chem. Educ.*, **89**(12), 1511–1514.

DeKorver B. K. and Towns M. H., (2015), General Chemistry Students' Goals for Chemistry Laboratory Coursework, *J. Chem. Educ.*, **92**(12), 2031–2037.

DeKorver B. K. and Towns M. H., (2016), Upper-level undergraduate chemistry students' goals for their laboratory coursework, *J. Res. Sci. Teach.*, **53**(8), 1198–1215.

Diekemper D., Schnick W. and Schwarzer S., (2019), Microwave Synthesis of a Prominent LED Phosphor for School Students: Chemistry's Contribution to Sustainable Lighting, *J. Chem. Educ.*, **96**(12), 3018–3024.

Dolin J., Black P., Harlen W. and Tiberghien A., (2018), Exploring Relations Between Formative and Summative Assessment, in Dolin J. and Evans R. (ed.), *Transforming Assessment: Through an Interplay Between Practice, Research and Policy*, Cham: Springer International Publishing, pp. 53–80.

Domin D. S., (1999), A review of laboratory instruction styles, *J. Chem. Educ.*, **76**(4), 543–547.

Domínguez Alfaro J. L., Gantois S., Blattgerste J., De Croon, R., Verbert, K., Pfeiffer, T. and Van Puyvelde, P., (2022), Mobile Augmented Reality Laboratory for Learning Acid–Base Titration, *J. Chem. Educ.*, **99**(2), 531–537.

Dood A. J., Johnson L. M. and Shorb J. M., (2018), Electronic Laboratory Notebooks Allow for Modifications in a General, Organic, and Biochemistry Chemistry Laboratory To Increase Authenticity of the Student Experience, *J. Chem. Educ.*, **95**(11), 1922–1928.

Dunnagan C. L., Dannenberg D. A., Cuales M. P., Earnest A. D., Gurnsey R. M. and Gallardo-Williams M. T., (2020), Production and Evaluation of a Realistic Immersive Virtual Reality Organic Chemistry Laboratory Experience: Infrared Spectroscopy, *J. Chem. Educ.*, **97**(1), 258–262.

Egambaram O., Hilton K., Leigh J., Richardson R., Sarju J., Slater A. and Turner B., (2022), The Future of Laboratory Chemistry Learning and Teaching Must be Accessible, *J. Chem. Educ.*, **99**(12), 3814–3821.

Ellegaard M., Damsgaard L., Bruun J. and Johannsen B. F., (2018), Patterns in the form of formative feedback and student response, *Assess. Eval. Higher Educ.*, **43**(5), 727–744.

Fay M. E., Grove N. P., Towns M. H. and Bretz S. L., (2007), A rubric to characterize inquiry in the undergraduate chemistry laboratory, *Chem. Educ. Res. Pract.*, **8**(2), 212–219.

Finne L. T., Gammelgaard B. and Christiansen F. V., (2021), Tid til læring i laboratoriet: farmaceutstuderendes opfattelse af tiden i laboratorieundervisningen, *Dansk Universitetspædagogisk Tidsskrift*, **16**, 43–58.

Finne L. T., Gammelgaard B. and Christiansen F. V., (2022), When the Lab Work Disappears: Students' Perception of Laboratory Teaching for Quality Learning, *J. Chem. Educ.*, **99**(4), 1766–1774.

Finne L. T., Gammelgaard B. and Christiansen F. V., (2023), Pharmacy students' conceptions of theory–practice relation in the analytical chemistry laboratory – a phenomenographic study, *Chem. Educ. Res. Pract.*, **24**(2), 428–436.

Finster D. C., (2021), RAMP: A Safety Tool for Chemists and Chemistry Students, *J. Chem. Educ.*, **98**(1), 19–24.

Flaherty A., (2022), The Chemistry Teaching Laboratory: A Sensory Overload Vortex for Students and Instructors? *J. Chem. Educ.*, **99**(4), 1775–1777.

Flaherty A., O'Dwyer A., Mannix-McNamara P. and Leahy J. J., (2017), The influence of psychological empowerment on the enhancement of chemistry laboratory demonstrators' perceived teaching self-image and behaviours as graduate teaching assistants, *Chem. Educ. Res. Pract.*, **18**(4), 710–736.

Flynn A. B. and Biggs R., (2012), The Development and Implementation of a Problem-Based Learning Format in a Fourth-Year Undergraduate Synthetic Organic and Medicinal Chemistry Laboratory Course, *J. Chem. Educ.*, **89**(1), 52–57.

Fortunato S., Bergstrom C. T., Börner K., Evans J. A., Helbing D., Milojević S., Petersen A. M., Radicchi F., Sinatra R., Uzzi B., Vespignani A., Waltman L., Wang D. and Barabási A.-L., (2018), Science of science, *Science*, **359**(6379), eaao0185.

Gallardo-Williams M. T. and Dunnagan C. L., (2022), Designing Diverse Virtual Reality Laboratories as a Vehicle for Inclusion of Underrepresented Minorities in Organic Chemistry, *J. Chem. Educ.*, **99**(1), 500–503.

Gallardo-Williams M., Morsch L. A., Paye C. and Seery M. K., (2020), Student-generated video in chemistry education, *Chem. Educ. Res. Pract.*, **21**(2), 488–495.

Galloway K. R., Malakpa Z. and Bretz S. L., (2016), Investigating Affective Experiences in the Undergraduate Chemistry Laboratory: Students' Perceptions of Control and Responsibility, *J. Chem. Educ.*, **93**(2), 227–238.

Gaynor J., (2021), *360° Lab Safety exercises*, ChemTube3D, Available at: **https://www.chemtube3d.com/chemistry-health-and-safety-360-exercises/**.

George-Williams S. R., Soo J. T., Ziebell A. L., Thompson C. D. and Overton T. L., (2018a), Inquiry and industry inspired laboratories: the impact on students' perceptions of skill development and engagements, *Chem. Educ. Res. Pract.*, **19**(2), 583–596.

George-Williams S. R., Ziebell A. L., Kitson R. R. A., Coppo P., Thompson C. D. and Overton T. L., (2018b), What do you think the aims of doing a practical chemistry course are?' A comparison of the views of students and teaching staff across three universities, *Chem. Educ. Res. Pract.*, **19**(2), 463–473.

George-Williams S., Carroll M.-R., Ziebell A., Thompson C. and Overton T. (2019a) Curtailing marking variation and enhancing feedback in large scale undergraduate chemistry courses through reducing academic judgement: a case study, *Assess. Eval. Higher Educ.*, **44**(6), 881–893.

George-Williams S. R., Karis D., Ziebell A. L., Kitson R. R. A., Coppo P., Schmid S., Thompson C. D. and Overton T. L. (2019b) Investigating student and staff perceptions of students' experiences in teaching laboratories through the lens of meaningful learning, *Chem. Educ. Res. Pract.*, **20**(1), 187–196.

George-Williams S. R., Ziebell A. L., Thompson C. D. and Overton T. L., (2020), Inquiry-, problem-, context- and industry- based laboratories: an investigation into the impact of large-scale, longitudinal redevelopment on student perceptions of teaching laboratories, *Int. J. Sci. Educ.*, **42**(3), 451–468.

Geragosian E. K., Zhu D., Skriloff M. and Shultz G. V., (2023), Chemistry graduate teaching assistants' teacher noticing, *Chem. Educ. Res. Pract.*, DOI: **10.1039/D3RP00003F**.

Gorman S. A., Holmes K., Brooke G., Pask C. M. and Mistry N., (2021), Repurposing an Introductory Organic and Inorganic Laboratory Course from the Focus on Teaching Theory to the Focus on Teaching Practical Technique, *J. Chem. Educ.*, **98**(6), 1910–1918.

Hamper B. C. and Meisel J. W., (2020), Introducing Nonscience Majors to Science Literacy via a Laboratory and Lecture Beer Brewing Course, *J. Chem. Educ.*, **97**(5), 1289–1294.

Hanauer D. I., Graham M. J., Sea-Phages, Betancur L., Bobrownicki A., Cresawn S. G., Garlena R. A., Jacobs-Sera D., Kaufmann N. and Pope W. H., (2017), An inclusive Research Education Community (iREC): Impact of the SEA-PHAGES program on research outcomes and student learning, *Proce. Natl. Acad. Sci. U. S. A.*, **114**(51), pp. 13531–13536.

Hancock L. M. and Hollamby M. J., (2020), Assessing the Practical Skills of Undergraduates: The Evolution of a Station-Based Practical Exam, *J. Chem. Educ.*, **97**(4), 972–979.

Harlen W. and James M., (1997), Assessment and Learning: differences and relationships between formative and summative assessment, *Assess. Educ.: Principles, Policy Pract.*, **4**(3), 365–379.

Hensiek S., DeKorver B. K., Harwood C. J., Fish J., O'Shea K. and Towns M., (2017), Digital Badges in Science: A Novel Approach to the Assessment of Student Learning, *J. Coll. Sci. Teach.*, **46**(3), 28.

Hill M. A., Overton T. L., Thompson C. D., Kitson R. R. A. and Coppo P., (2019), Undergraduate recognition of curriculum-related skill development and the skills employers are seeking, *Chem. Educ. Res. Pract.*, **20**(1), 68–84.

Hill M. A., Overton T., Kitson R. R., Thompson C. D., Brookes R. H., Coppo P. and Bayley L., (2022), They help us realise what we're actually gaining': The impact on undergraduates and teaching staff of displaying transferable skills badges, *Active Learn. Higher Educ.*, **23**(1), 17–34.

Hounsell D. and Hounsell J., (2007), Teaching-learning environments in contemporary mass higher education, *BJEP monograph series II, number 4: Student learning and university teaching: Vol. 111*, British Psychological Society, pp. 91–111.

Hyde J., (2019), Design of a three year laboratory programme for international delivery, in Seery M. K. and McDonnell C. (ed.), *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton*, Dublin: Creathach Press, pp. 405–420.

Hyde J., Wright J. S. and Xie A., (2023), Progression from Chinese High School onto a TransNational Chinese-UK University joint BSc degree in chemistry; an international study focussing on laboratory practical skills, *Chem. Educ. Res. Pract.*, DOI: **10.1039/D3RP00099K**.

Jacobsen F. E., (2023), Use of Student-Generated Technique Videos to Increase Laboratory Skills in an Online General Chemistry Laboratory, *J. Chem. Educ.*, **100**(4), 1460–1465.

Johansen M. W. and Christiansen F. V., (2020), Handling Anomalous Data in the Lab: Students' Perspectives on Deleting and Discarding, *Sci. Eng. Ethics*, **26**(2), 1107–1128.

Johnstone A. H. and Wham A. J. B., (1982), The demands of practical work, *Educ. Chem.*, **19**(3), 71–73.

Jordan T. C., Burnett S. H., Carson S., Caruso S. M., Clase K., DeJong R. J., Dennehy J. J., Denver D. R., Dunbar D. and Elgin S. C., (2014), A broadly implementable research course in phage discovery and genomics for first-year undergraduate students, *mBio*, **5**(1), e01051–13.

Jørgensen J. T., Gammelgaard B. and Christiansen F. V., (2023), Teacher Intentions vs Student Perception of Feedback on Laboratory Reports, *J. Chem. Educ.*, **100**(10), 3764–3773.

Kasting B. J., Bowser A. K., Anderson-Wile A. M. and Wile B. M., (2015), Synthesis and Metalation of a Ligand: An Interdisciplinary Laboratory Experiment for Second-Year Organic and Introductory Inorganic Chemistry Students, *J. Chem. Educ.*, **92**(6), 1103–1109.

Katja S. and Olga K., (2015), Using Problem-Based Learning in a Chemistry Practical Class for Pharmacy Students and Engaging Them with Feedback, *Am. J. Pharm. Educ.*, **79**(9), 141.

Kelley E. W., (2021), LAB Theory, HLAB Pedagogy, and Review of Laboratory Learning in Chemistry during the COVID-19 Pandemic, *J. Chem. Educ.*, **98**(8), 2496–2517.

Kelly O. C. and Finlayson O. E., (2007), Providing solutions through problem-based learning for the undergraduate 1st year chemistry laboratory, *Chem. Educ. Res. Pract.*, **8**(3), 347–361.

Kirschner P. and Neelen M., (2018), *No feedback, no learning*, 3-Star Learning Experiences, Available at: **https://3starlearningexperiences.wordpress.com/2018/06/05/no-feedback-no-learning/**.

Kirton S. B., Al-Ahmad A. and Fergus S., (2014), Using Structured Chemistry Examinations (SChemEs) As an Assessment Method To Improve Undergraduate Students' Generic, Practical, and Laboratory-Based Skills, *J. Chem. Educ.*, **91**(5), 648–654.

Koesdjojo M. T., Pengpumkiat S., Wu Y., Boonloed A., Huynh D., Remcho T. P. and Remcho V. T., (2015), Cost Effective Paper-Based Colorimetric Microfluidic Devices and Mobile Phone Camera Readers for the Classroom, *J. Chem. Educ.*, **92**(4), 737–741.

Lau P. N., (2020), Enhancing formative and self-assessment with video playback to improve critique skills in a titration laboratory, *Chem. Educ. Res. Pract.*, **21**(1), 178–188.

Lawrie G. A., Grøndahl L., Boman S. and Andrews T., (2016), Wiki Laboratory Notebooks: Supporting Student Learning in Collaborative Inquiry-Based Laboratory Experiments, *J. Sci. Educ. Technol.*, **25**(3), 394–409.

Lim K. F., (2009), Doing it again, thoughtfully: Using feedback on draft reports to improve learning outcomes, *Aust. J. Educ. Chem.*, **70**, 11–16.

Lim K. F., (2015), Improving laboratory learning through self and peer assessment of laboratory reports, *Int. J. Innovation Sci. Math. Educ.*, **23**(2), 59–73.

Loughlin W. A. and Cresswell S. L., (2021), Online Safety Quiz for Interactive Revision Reveals Areas for Laboratory Safety Development in Second-Year Undergraduate Chemistry, *J. Chem. Educ.*, **98**(1), 218–223.

MacKay J. A. and Wetzel N. R., (2014), Exploring the Wittig Reaction: A Collaborative Guided-Inquiry Experiment for the Organic Chemistry Laboratory, *J. Chem. Educ.*, **91**(5), 722–725.

Marin L. S., Muñoz-Osuna F. O., Arvayo-Mata K. L. and Álvarez-Chávez C. R., (2019), Chemistry laboratory safety climate survey (CLASS): A tool for measuring students' perceptions of safety, *J. Chem. Health Saf.*, **26**(6), 3–11.

Marincean S., Smith S. R., Fritz M., Lee B. J. and Rizk Z., (2012), NMR Studies of Structure–Reactivity Relationships in Carbonyl Reduction: A Collaborative Advanced Laboratory Experiment, *J. Chem. Educ.*, **89**(12), 1591–1594.

McDonnell C., O'Connor C. and Seery M. K., (2007), Developing practical chemistry skills by means of student-driven problem based learning mini-projects, *Chem. Educ. Res. Pract.*, **8**(2), 130–139.

McGarvey D. J., (2020), A Data-Pooling Laboratory Activity to Investigate the Influence of Ionic Strength on the Solubility of $CaSO_4 \cdot 2H_2O(s)$, *J. Chem. Educ.*, **97**(2), 517–521.

McKnelly K. J., Howitz W. J., Thane T. A. and Link R. D., (2023), Specifications Grading at Scale: Improved Letter Grades and Grading-Related Interactions in a Course with over 1,000 Students, *J. Chem. Educ.*, 2023, **100**(9), 3179–3193.

Miller D. K. and Lang P. L., (2016), Using the Universal Design for Learning Approach in Science Laboratories To Minimize Student Stress, *J. Chem. Educ.*, **93**(11), 1823–1828.

Mistry N., Fitzpatrick C. and Gorman S., (2016), Design Your Own Workup: A Guided-Inquiry Experiment for Introductory Organic Laboratory Courses, *J. Chem. Educ.*, **93**(6), 1091–1095.

Montgomery C. A. and Goll J. M., (2023), Show Me You Can Do It: Practical Examinations for Senior Organic Chemistry Laboratory Courses, *J. Chem. Educ.*, **100**(6), 2253–2261.

Moore C., Smith S. and Avner R. A., (1980), Facilitation of laboratory performance through CAI, *J. Chem. Educ.*, **57**(3), 196–198.

Moozeh K., Farmer J., Tihanyi D., Nadar T. and Evans G. J., (2019), A Prelaboratory Framework Toward Integrating Theory and Utility Value with Laboratories: Student Perceptions on Learning and Motivation, *J. Chem. Educ.*, **96**(8), 1548–1557.

Moraes E. P., da Silva N. S. A., de Morais C. D. L. M., das Neves L. S. and de Lima K. M. G., (2014), Low-Cost Method for Quantifying Sodium in Coconut Water and Seawater for the Undergraduate Analytical Chemistry Laboratory: Flame Test, a Mobile Phone Camera, and Image Processing, *J. Chem. Educ.*, **91**(11), 1958–1960.

Moraes E. P., Confessor M. R. and Gasparotto L. H. S., (2015), Integrating Mobile Phones into Science Teaching To Help Students Develop a Procedure To Evaluate the Corrosion Rate of Iron in Simulated Seawater, *J. Chem. Educ.*, **92**(10), 1696–1699.

Mundy C. and Potgieter M., (2020), Hands-On Spectroscopy: Inside and Outside the First-Year Laboratory, *J. Chem. Educ.*, **97**(6), 1549–1555.

Mundy C. E., Potgieter M. and Seery M. K., (2023), A design-based research approach to improving pedagogy in the teaching laboratory, *Chem. Educ. Res. Pract.*, DOI: 10.1039/D3RP00134B.

Murphy K. C., Dilip M., Quattrucci J. G., Mitroka S. M. and Andreatta J. R., (2019), Sustainable Consumer Choices: An Outreach Program Exploring the Environmental Impact of Our Consumer Choices Using a Systems Thinking Model and Laboratory Activities, *J. Chem. Educ.*, **96**(12), 2993–2999.

Musgrove A., (2023), '"Buddy check" peer observation activity for hands-on learning in analytical chemistry laboratories, *Anal. Bioanal. Chem.*, **415**(17), 3299–3303.

Nordmann E., Horlin C., Hutchison J., Murray J.-A., Robson L., Seery M. K. and MacKay J. R. D., (2020), Ten simple rules for supporting a temporary online pivot in higher education, *PLoS Comput. Biol.*, **16**(10), e1008242.

O'Donoghue J. and Fitzsimmons L., (2022), Simplified Low-Cost LED Nephelometer and Turbidity Experiments for Practical Teaching, *J. Chem. Educ.*, **99**(3), 1304–1312.

Pagano T. and Quinsland L. K., (2007), Pedagogical Applications of Instant Messaging Technology for Deaf and Hard-of-Hearing Students in the Science Classroom, *J. Sci. Educ. Stud. Disabil.*, **12**(1), 33–46.

Paschalidou K., Salta K. and Koulougliotis D., (2022), Exploring the connections between systems thinking and green chemistry in the context of chemistry education: A scoping review, *Sustainable Chem. Pharm.*, **29**, 100788.

Prades A. and Espinar S. R., (2010), Laboratory assessment in chemistry: an analysis of the adequacy of the assessment process, *Assess. Eval. Higher Educ.*, **35**(4), 449–461.

Prosser M. and Trigwell K., (1999), *Understanding learning and teaching: The experience in higher education*, McGraw-Hill Education, UK.

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

Rabago Smith M., McAllister R., Newkirk K., Basing A. and Wang L., (2012), Development of an Interdisciplinary Experimental Series for the Laboratory Courses of Cell and Molecular Biology and Advance Inorganic Chemistry, *J. Chem. Educ.*, **89**(1), 150–155.

Read D. and Barnes S., (2015), *Review of A-level Chemistry Content 2015*, Southampton, Available at: https://edshare.soton.ac.uk/14806/.

Reid N. and Shah I., (2007), The role of laboratory work in university chemistry, *Chem. Educ. Res. Pract.*, **8**(2), 172–185.

Reynders G., Suh E., Cole R. S. and Sansom R. L., (2019), Developing Student Process Skills in a General Chemistry Laboratory, *J. Chem. Educ.*, **96**(10), 2109–2119.

Reynders G., Lantz J., Ruder S. M., Stanford C. L. and Cole R. S., (2020), Rubrics to assess critical thinking and information processing in undergraduate STEM courses, *Int. J. STEM Educ.*, **7**(9), 1–15.

Reynders M., Pilcher L. A. and Potgieter M., (2023), Teaching and Assessing Systems Thinking in First-Year Chemistry, *J. Chem. Educ.*, **100**(3), 1357–1365.

Richards-Babb M., Penn J. H. and Withers M., (2014), Results of a Practicum Offering Teaching-Focused Graduate Student Professional Development, *J. Chem. Educ.*, **91**(11), 1867–1873.

Rodriguez J.-M. G. and Towns M. H., (2018), Modifying Laboratory Experiments To Promote Engagement in Critical Thinking by Reframing Prelab and Postlab Questions, *J. Chem. Educ.*, **95**(12), 2141–2147.

Royal Society of Chemistry, (2022), *Sustainable laboratories: A community-wide movement toward sustainable laboratory practices*, Cambridge, Available at: https://www.rsc.org/policy-evidence-campaigns/environmental-sustainability/sustainability-reports-surveys-and-campaigns/sustainable-laboratories/.

Russell C. B. and Weaver G. C., (2011), A comparative study of traditional, inquiry-based, and research-based laboratory curricula: impacts on understanding of the nature of science, *Chem. Educ. Res. Pract.*, **12**(1), 57–67.

Santos Santos, E., Gavilán García, I. C., Lejarazo Gómez, E. F. and Vilchis-Reyes, M. A., (2010), Synthesis of Aryl-Substituted 2,4-Dinitrophenylamines: Nucleophilic Aromatic Substitution as a Problem-Solving and Collaborative-Learning Approach, *J. Chem. Educ.*, **87**(11), 1230–1232.

Sarju J. P. and Jones L. C., (2022), Improving the Equity of Undergraduate Practical Laboratory Chemistry: Incorporating Inclusive Teaching and Accessibility Awareness into Chemistry Graduate Teaching Assistant Training, *J. Chem. Educ.*, **99**(1), 487–493.

Schmidt-McCormack J. A., Muniz M. N., Keuter E. C., Shaw S. K. and Cole R. S., (2017), Design and implementation of instructional videos for upper-division undergraduate laboratory courses, *Chem. Educ. Res. Pract.*, **18**(4), 749–762.

Schön D., (1983), *The Reflective Practitioner: How Professionals Think in Action*, New York: Basic Books.

Schwarz G., Picotti V., Bleiner D. and Gundlach-Graham A., (2020), Incorporating a Student-Centered Approach with Collaborative Learning into Methods in Quantitative Element Analysis, *J. Chem. Educ.*, **97**(10), 3617–3623.

Scoggin J. and Smith K. C., (2023), Enabling general chemistry students to take part in experimental design activities, *Chem. Educ. Res. Pract.*, **24**, 1229–1242.

Scott C., Wisdom N.-H., Coulter K., Bardin S., Strap J. L. and Trevani L., (2023), Interdisciplinary Undergraduate Laboratory for an Integrated Chemistry/Biology Program: Synthesis of Silver Nanoparticles (AgNPs)-Cellulose Composite Materials with Antimicrobial Activity, *J. Chem. Educ.*, **100**(4), 1446–1454.

Seery M. K., (2017), *There's a badge for that*, Education in Chemistry: Royal Society of Chemistry, Available at: **https://edu.rsc.org/feature/theres-a-badge-for-that/2500444.article**.

Seery M. K., (2020), Establishing the Laboratory as the Place to Learn How to Do Chemistry, *J. Chem. Educ.*, **97**(6), 1511–1514.

Seery M. K., Agustian H. Y., Doidge E. D., Kucharski M. M., O'Connor H. M. and Price A., (2017), Developing laboratory skills by incorporating peer-review and digital badges, *Chem. Educ. Res. Pract.*, **18**, 403–419.

Seery M. K., Agustian H. Y. and Lambert T. O., (2019a), Teaching and assessing technical competency in the chemistry laboratory, in Seery M. K. and McDonnell C. (ed.), *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton*, Dublin: Creathach Press, pp. 349–362.

Seery M. K., Agustian H. Y. and Zhang X., (2019b), A Framework for Learning in the Chemistry Laboratory, *Isr. J. Chem.*, **59**(6–7), 546–553.

Seery M. K., Jones A. B., Kew W. and Mein T., (2019c), Unfinished Recipes: Structuring Upper-Division Laboratory Work To Scaffold Experimental Design Skills, *J. Chem. Educ.*, **96**(1), 53–59.

Shultz G. V. and Li Y., (2016), Student Development of Information Literacy Skills during Problem-Based Organic Chemistry Laboratory Experiments, *J. Chem. Educ.*, **93**(3), 413–422.

Simpson P., (1973), Videotapes in laboratory teaching, *Educ. Chem.*, **10**(5), 174–175.

Spagnoli D., Wong L., Maisey S. and Clemons T. D., (2017), Prepare, Do, Review: a model used to reduce the negative feelings towards laboratory classes in an introductory chemistry undergraduate unit, *Chem. Educ. Res. Pract.*, **18**(1), 26–44.

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

Spencer-Briggs J. L. and Rourke J. P., (2023), A New Bridging "Introduction to University Chemistry" Module for Cardiff University, *J. Chem. Educ.*, **100**(2), 554–563.

Tapper J., (1999), Topics and manner of talk in undergraduate practical laboratories, *Int. J. Sci. Educ.*, **21**(4), 447–464.

Taylor D., Rogers A. L. and Veal W. R., (2009), Using Self-Reflection To Increase Science Process Skills in the General Chemistry Laboratory, *J. Chem. Educ.*, **86**(3), 393.

Thomson P. I. T. and Lamie P., (2022), Introducing Elements of Inquiry and Experimental Design in the First Year of an Undergraduate Laboratory Program, *J. Chem. Educ.*, **99**(12), 4118–4123.

Towns M., Harwood C. J., Robertshaw M. B., Fish J. and O'Shea K., (2015), The Digital Pipetting Badge: A Method To Improve Student Hands-On Laboratory Skills, *J. Chem. Educ.*, **92**(12), 2038–2044.

Tremlett R., (1972), *An investigation into the development of a program of practical work in chemistry for undergraduates*, PhD, University of East Anglia.

Van Dyke A. R. and Smith-Carpenter J., (2017), Bring Your Own Device: A Digital Notebook for Undergraduate Biochemistry Laboratory Using a Free, Cross-Platform Application, *J. Chem. Educ.*, **94**(5), 656–661.

Varadarajan S. and Ladage S., (2022), Exploring the role of scaffolds in problem-based learning (PBL) in an undergraduate chemistry laboratory, *Chem. Educ. Res. Pract.*, **23**(1), 159–172.

Veale C. G. L., Jeena V. and Sithebe S., (2020), Prioritizing the Development of Experimental Skills and Scientific Reasoning: A Model for Authentic Evaluation of Laboratory Performance in Large Organic Chemistry Classes, *J. Chem. Educ.*, **97**(3), 675–680.

Veiga N., Luzardo F., Irving K., Rodríguez-Ayán M. N. and Torres J., (2019), Online pre-laboratory tools for first-year undergraduate chemistry course in Uruguay: student preferences and implications on student performance, *Chem. Educ. Res. Pract.*, **20**(1), 229–245.

Walker J. P. and Sampson V., (2013), Learning to argue and arguing to learn: Argument-driven inquiry as a way to help undergraduate chemistry students learn how to construct arguments and engage in argumentation during a laboratory course, *J. Chem. Educ.*, **50**(5), 561–596.

Walters A. U. C., Lawrence W. and Jalsa N. K., (2017), Chemical laboratory safety awareness, attitudes and practices of tertiary students, *Saf. Sci.*, **96**, 161–171.

Watts F. M. and Rodriguez J.-M. G., (2023), A Review of Course-Based Undergraduate Research Experiences in Chemistry, *J. Chem. Educ.*, **100**(9), 3261–3275.

West J. K., Franz J. L., Hein S. M., Leverentz-Culp H. R., Mauser J. F., Ruff E. F. and Zemke J. M., (2023), An Analysis of AI-Generated Laboratory Reports across the Chemistry Curriculum and Student Perceptions of ChatGPT, *J. Chem. Educ.*, 2023, **100**(11), 4351–4359.

Widanski B., Thompson J. A. and Foran-Mulcahy K., (2020), Improving Students' Oral Scientific Communication Skills through Targeted Instruction in Organic Chemistry Lab, *J. Chem. Educ.*, **97**(10), 3603–3608.

Williams N. D., Gallardo-Williams M. T., Griffith E. H. and Bretz S. L., (2022), Investigating Meaningful Learning in Virtual Reality Organic Chemistry Laboratories, *J. Chem. Educ.*, **99**(2), 1100–1105.

Winberg T. M. and Berg C. A. R., (2007), Students' cognitive focus during a chemistry laboratory exercise: Effects of a computer-simulated prelab, *J. Res. Sci. Teach.*, **44**(8), 1108–1133.

Wuchty S., Jones B. F. and Uzzi B., (2007), The increasing dominance of teams in production of knowledge, *Science*, **316**(5827), 1036–1039.

Xu H. and Talanquer V., (2013), Effect of the Level of Inquiry on Student Interactions in Chemistry Laboratories, *J. Chem. Educ.*, **90**(1), 29–36.

Zhu B., Feng M., Lowe H., Kesselman J., Harrison L. and Dempski R. E., (2018), Increasing Enthusiasm and Enhancing Learning for Biochemistry-Laboratory Safety with an Augmented-Reality Program, *J. Chem. Educ.*, **95**(10), 1747–1754.

Ziebell A., George-Williams S. R., Danczak S. M., Ogunde J. C., Hill M. A., Fernandez K., Sarkar M., Thompson C. D. and Overton T. L., (2019), Overturning a laboratory course to develop 21st century skills, in Seery M. K. and McDonnell C. (ed.), *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton*, Dublin: Creathach Press, pp. 363–376.