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A framework for learning in the chemistry laboratory

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Designing laboratory activities is a real challenge for those working in higher education. There is often an acknowledged frustration with the status quo, but a lack of clear guidance on what strategies might be useful in considering a redesign. This article aims to address the question: *what considerations should be taken into account when designing a laboratory activity?* To address it, we first describe an overarching framework for laboratory learning, describing it as a complex learning environment. The reason for this is that two clear overarching guidelines emerge – the first is that the laboratory curriculum should be structured so that each new challenge for student is adequately supported by their prior learning so that they can draw on their knowledge to address the new learning situation, and the second is that guidelines for the kinds of preparation for laboratory learning emerge. Based on this framework, we advocate four core principles for laboratory learning that should be considered when designing a laboratory activity regarding the overall purpose, the role of preparation, the teaching of technique, and the consideration of affective dimensions of learning. We illustrate this framework in practice with examples from our own practice, with suggestions on using the literature on laboratory education as a source for curriculum reform within an institution.

Introduction

Rationale for this overview

Learning in the laboratory is a core component of the chemistry curriculum. However despite its exalted status and long-standing place in our teaching, there is continuing dissatisfaction among educators and students about laboratory learning. Concerns about the extent of learning in laboratories raised in the 1980s,[1] echoed in reviews in the early 2000s,[2] and still found in research in the last few years[3] highlight that there is a continuing demand for reconsideration of approaches to how we incorporate practical work into a chemistry curriculum. The literature on chemistry laboratory education is vast, spanning over a century, so that it is overwhelming to practitioners looking to improve their laboratory practice.

In this overview, we aim to speak directly to those practitioners looking to answer the question: *what considerations should be taken into account when designing a laboratory activity?*

This overview aims to correspond our thoughts on how we would answer this question. In doing so, we draw on some of the enormous body of literature on laboratory education, as well as current research, including our own. We shy away from the specific identities of particular laboratory approaches such as expository or inquiry, discovery or problem-based. This is not because they are not helpful – indeed some enormously useful work has been done in elaborating on these approaches[4] – but because for the particular audience of this piece, we intend to communicate instead the salient features of what an effective learning environment might look like, rather than how they are categorised in the educational literature. We acknowledge that there is no one "perfect approach", because curricula and students and stage of learning will all differ for any particular context, and hence influence what is possible in any particular laboratory classroom. Conscious of this, we do believe that there are some salient features of laboratory education that are in general terms universal to all effective laboratory learning scenarios. We list them here, and elaborate on them for the rest of our article. We aim to draw these aspects together into one framework that aims to incorporate the various components we advocate, that we hope will act as a useful scaffold for those wishing to reconsider laboratory education in their own settings.

Learning from research – key features of laboratory learning

The literature on laboratory learning offers a multitude of opinions and approaches, sometimes contradictory, about effective laboratory learning. In order to position ourselves from the outset, we tend to agree with the following guiding principles regarding laboratory learning:

1. The overarching purpose of laboratory learning is to teach learners *how* to 'do' science.[5]
2. Preparing students for learning in the laboratory is beneficial.[6]
3. Explicit consideration needs to be given to teaching experimental techniques.[7]
4. Consideration of learners' emotions, motivations, and expectations is imperative in laboratory settings.[8]

Listing of these principles shows just how challenging the task of designing an effective laboratory curriculum can be. If we were to take a snapshot of a laboratory setting, the plethora of questions facing educators becomes clearer (Table 1).

Table 1

Questions about learning before the laboratory	**Questions about learning in the laboratory**	**Questions about learning after the laboratory**
What information should students know before entering a laboratory class?	How much information is presented to students regarding the work they need to complete in the laboratory?	What information is provided to students about how they should interpret/analyse their results, and how does this build on from pre-laboratory work?
How is this information presented to students?	How do students know how to complete any procedures/ techniques required?	Are students provided with exemplars or protocols to guide their assessed work?
How can students check their understanding of advance information?	What is the role of teaching assistants in the laboratory?	How is consistency of marking assured?
Is it clear to the students how they can use what they know for the laboratory session?	Is there an opportunity to test hypothesis/build on results in the laboratory?	What extent of feedback is provided and what are students asked to do with that feedback?
	How should students document their learning in the laboratory?	
	How can students check their understanding in the laboratory session?	

In answering the kinds of questions raised in designing laboratory work for students, the literature is clear that even slight variations in how they are answered can lead to very different laboratory experiences.[4c] The challenge for those responsible, usually academic staff running laboratory courses, is to know both what kinds of answers are appropriate, and what effect the chosen approaches will have on learning. The staff member running the laboratory class is of key importance, as is it their interpretation of how a laboratory class runs that will have most impact on the laboratory approach, regardless of curriculum specification.[9] This in turn requires quite an extensive knowledge of the literature, which leads us back to the original issues mentioned at the head of the article – academic staff becoming overwhelmed by the volume of literature on laboratory learning. We believe that this problem, along with the actual work of designing new experiments, is a significant reason why laboratory teaching approaches are so resistant to change.

A framework for laboratory learning

Before we address the guiding principles in detail, we first intend to describe an overarching framework for learning in the laboratory. The reason for this is that whatever purpose or activity we intend the laboratory to be, it is valuable to be able to align it with an overarching framework so that we have guidelines to base our approaches to supporting and challenging students in an appropriate way. Drawing from the educational psychology literature,[10] we propose the description of laboratory learning as a *complex learning environment*. While not intended for laboratory learning specifically, we find this framework useful because it helps describe why learning in laboratory is different, and challenging, and how we can best support students in this environment.

A complex learning environment in general terms is one that has the following characteristics.

(i) Complex learning aims at the integration of knowledge, skills, and attitudes.

(ii) Complex learning involves the coordination of qualitatively different constituent skills.

(iii) Complex learning requires the transfer of what is learned to real settings.

We consider that these characteristics map on well to the aims and requirements of laboratory learning. However, the benefit of aligning with this framework is not so much in the description of the environment, but in what the recommendations are for supporting learning in this environment are. This support falls into two categories.

The first regards *supporting learning* in this environment. What makes learning *complex* is not the particular difficulty of any one component, but rather the process of integrating different components together to apply it in the new scenario. Therefore learners may be very good chemists, or may be very good at using a particular instrument, but in completing an experiment they need to know how to bring together the knowledge from these different areas and apply it to a new scenario. The psychologists who describe this environment advocate that we assist learners in doing this by defining the whole task so the integration aspects required is made clearer, and in developing a curriculum, we sequence learners' engagement with the challenge from a simple to complex way. This means learners will have the opportunity to previously understand and work the task being set in any laboratory setting that they can build on in approaching this more complicated task. We illustrate this with examples from our own case studies below, but the general cliché of "being able to walk before you can run" applies. In any learning scenario, we need to ensure that students have had practice at the constituent components necessary as well as a simpler version of the challenge they are about to take.

The second category provides more detail on the kinds of information that learners need to draw on when working in a complex learning environment. With the typical queries that arise in laboratory teaching, shown in Table 1, there were lots of cases where the learner needs to draw on some information – chemical knowledge, knowledge about how to operate instruments, knowledge about data processing, etc. The psychologists who describe this environment advocate that we distinguish between information that is necessary to give students a basis for understanding the experiment and the rationale for the work being conducted ("supportive information") and information that is necessary to know how to carry out particular procedures ("procedural information").[10] They argue that supportive information be provided in advance of the learning situation so that learners can draw on this knowledge in understanding the work being conducted and the rationale for particular approaches/instrumentation, and procedural information be provided as necessary in the learning situation, so that it is available particular procedural steps are being carried out. We have elaborated in much more detail previously about considering the laboratory as a complex learning environment,[6] and describe some of the implications for this below. We proceed now to describe key considerations of learning in the laboratory and their alignment with this framework.

Principles of Laboratory Learning

We elaborate below on the principles highlighted at the outset. The purpose here is not to be overly didactic, but to raise the issues that should be considered when decisions about the nature of laboratory curriculum design are being made.

1. The overarching purpose of laboratory learning is to teach learners how to 'do' science.

There is a large literature on the purpose of practical work, and indeed it is a useful exercise for those involved in teaching a group of students in a laboratory setting to conclude their own list of what they intend the laboratory session to achieve. It is likely that these purposes will align with many of the aims listed in Table 2.

A common aim of practical work, either formally stated or assumed by either faculty or students, is that laboratory work is useful to confirm theory in lectures has little basis. Kirschner and Meesters' work, which set the scene for many subsequent reforms in the late twentieth and early twenty-first century, described this purpose as an inefficient use of the laboratory.[5b]

Table 2: Some aims of practical work reported in the literature

Tamir (1976)[11]	**Kirschner and Meester (1988)[5b]**	**Carnduff and Reid (2003)[12] and Reid and Shah (2007)[13]**
Skills: e.g., manipulative, inquiry, investigative, organizational, communicative **Concepts:** e.g., data, hypothesis, theoretical model, taxonomic category **Cognitive abilities:** e.g., critical thinking, problem solving, application, analysis, synthesis, evaluation, decision making, creativity **Understanding the nature of science:** e. g., the scientific enterprise, the scientists and how they work, the existence of a multiplicity of scientific methods, the interrelationships between science and technology and among various disciplines of science **Attitudes:** e.g., curiosity, interest, risk taking, objectivity, precision, perseverance, satisfaction, responsibility, consensus and collaboration, confidence in scientific knowledge, self-reliance, liking science.	- To formulate hypotheses. - To solve problems. - To use knowledge and skills in unfamiliar situations. - To design simple experiments to test hypotheses. - To use laboratory skills in performing (simple) experiments. - To interpret experimental data. - To describe clearly the experiment. - To remember the central idea of an experiment over a significantly long period of time.	**Skills relating to learning chemistry.** There is opportunity to make chemistry real, to illustrate ideas and concepts, to expose theoretical ideas to empirical testing, to teach new chemistry. **Practical skills.** There is opportunity to handle equipment and chemicals, to learn safety procedures, to master specific techniques, to measure accurately, to observe carefully. **Scientific skills.** There is opportunity to learn the skills of observation and the skills of deduction and interpretation. There is the opportunity to appreciate the place of the empirical as a source of evidence in enquiry and to learn how to devise experiments which offer genuine insights into chemical phenomena. **General skills.** There are numerous useful skills to be gained: team working, reporting, presenting and discussing, time management, developing ways to solve problems.

Indeed, the major review of laboratory education by Hofstein and Lunetta in 2004 found that there was "sparse data from carefully designed and conducted studies" to support the hypothesis that laboratory education is essential for understanding science.[2] In their work on developing practical work for school science, Woolnaugh and Allsop argue for cutting the "Gordian Knot" between practical work and teaching theory; and to

> *stop using practical work as a subservient strategy for teaching scientific concepts and knowledge. There are self-sufficient reasons for doing practical work in science, and neither these, nor the aims concerning the teaching and understanding of scientific knowledge, are well served by the continua linking of practical work to the content syllabus of science [p. 39].*[5d]

Furthermore, the approach is plagued with implementation problems. For example, in laboratories where there is limited equipment, students “rotate” around experiments over the course of the laboratory programme, covering a different experiment each week. This scenario, often found in physical chemistry laboratories, can lead to frustration on the part of students, as they often have not completed the lecture theory associated with the experiment that the experiment is supposed to be verifying. Even if it was demonstrated that laboratories somehow influence or enhance learning of a particular topic covered in lectures, there remains a question of selection of topics to be covered within the limited time-frame imposed by practical sessions.

Kirschner, drawing on Woolnough,[5d] proposes a new basis for practical science incorporating three components which focus on the act of learning how to do science, consisting of:[5a]

1. To **develop specific skills** such as observation, manipulation, planning and execution and interpretation skills.
2. To **develop an academic approach** to working, by learning how a scientist works through a problem.
3. To **experience phenomena** in developing a ‘tacit’ knowledge about working in the laboratory.

Kirschner argues that practical work should be about teaching about how to do science, rather than doing science and therefore any laboratory instruction must enable students to learn the process of doing science (inquiry, interpretation, revision) in a highly structured way. In the complex learning environment framework, we can frame this in terms of considering whether the activity builds on previous work where leaners have had the opportunity to try a simpler version of the task being considered? For example, if a laboratory activity is looking to teach students about learning how to use a particular chromatographic technique, have they previously completed an activity where the constituent skills, such as determining retention times of possible contaminants or changing eluent composition? This might mean that an advanced practical on using gas chromatography builds on an earlier practical of using thin layer chromatography. The teacher should be clear about what additional challenges are unique to the more advanced setting, and how the previous setting prepared learners for drawing together the necessary components in a simpler way. *The additional level of difficulty should be easily identifiable* when designing new laboratory activities. Designing activities that introduce too many new components to learners at one time will overwhelm learning opportunities.

2. Preparing students for learning in the laboratory is beneficial.

We have previously described in a large-scale review the reports of pre-laboratory activities, which tended to fall into the types of categories shown in Figure 1.[6] Firstly, they have been used to introduce chemical concepts, using approaches such as pre-laboratory lectures, pre-laboratory quizzes, and pre-laboratory discussion. Secondly, they have been used to introduce laboratory techniques, using approaches such as interactive simulations, technique videos, mental preparation, and safety information. Lastly, they have been used to address affective aspects such as confidence and motivation.

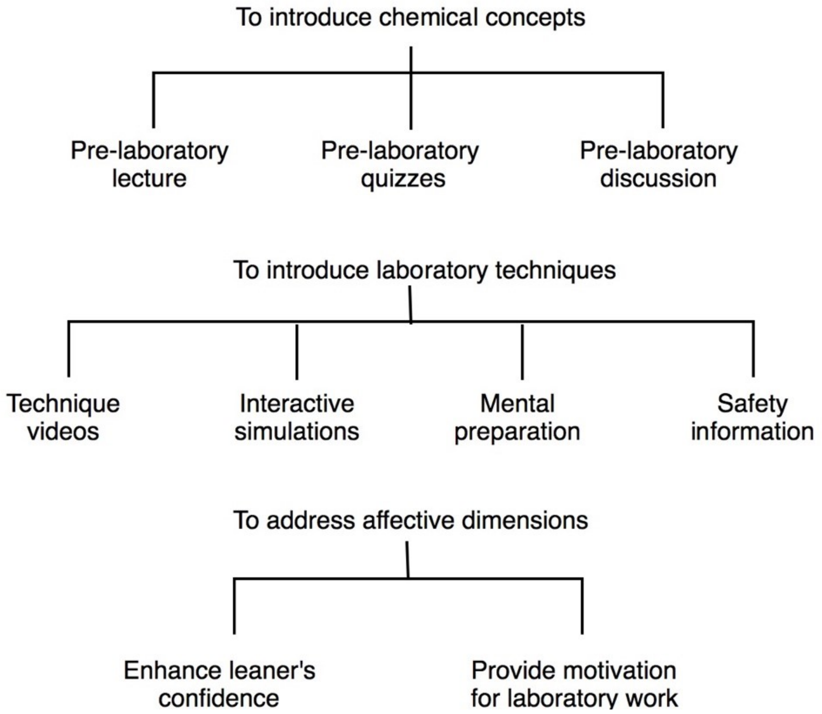

Figure 1. Summary of rationales for pre-laboratory activities and the reported approaches

The general outcome of the reviewed literature was that pre-laboratory activities have acknowledged benefit, both where they were intended (improved use of technique, or improved understanding of underpinning chemistry concepts), as well as unintended (improved confidence in laboratory tasks, improved efficiency in laboratory work). Much of the literature did not align to any particular educational framework, beyond the sense that there was a need for some element of preparation. Those that did tended to consider it in the context of cognitive load,[14] an issue previously raised by Johnstone regarding learning in the laboratory.[1, 15] This work argued that given the information associated with the kinds of challenges listed in Table 1, that it was no surprise that students felt overwhelmed and tended to work through the laboratory with little intellectual engagement with the laboratory work.

We have further elaborated on the role of cognitive load by considering the laboratory as a complex learning environment, as described above. In this context, we can ask: how are students prepared for any particular laboratory experiment, and what information will the learner have to draw on intellectually in the laboratory setting? When and how is this provided? Preparative activities with a clear purpose of preparing students for the components that they will need to draw on in the laboratory setting should be made available to students, and the complex learning environment gives useful guidance on distinguishing between supportive information that should be presented in advance, and procedural information that is suitable “just in time”.

3. Explicit consideration needs to be given to teaching experimental techniques

Learning laboratory techniques is a core component of practical science and is necessary both for the purpose of developing laboratory competence and being able to use techniques in experimentation. The typical approach tends to be implicit – students are set challenges to complete, whereby it is intended that their use of approaches or instrumentation will allow them to develop competency. We reject this model of teaching chemical technique. In a major historical review of teaching chemical technique,[16] DeMeo refers to “elbow instruction” – the traditional guide on the side teaching leaners about particular approaches. As class sizes increase, the extent to which such individualised attention can be given to students is limited. In addition, because the typical assessment format of laboratory work tends not to directly assess technique, students do not get an explicit opportunity to test their understanding and correctness of approach.

Typical strategies to address this are to indirectly assess chemical technique by assessing the quality of output (e.g. chemical purity)[17] or to have laboratory tests where students demonstrate their ability to complete techniques while being observed.[18] Such approaches have been criticized for “loading up” feedback,[19] giving students feedback after the assessment event, rather than during it. Instead we embrace a formative assessment model, guided by the principle of formative assessment:[20] that students must develop the capacity to monitor the quality of their work during its production. With genuine formative assessment, this means that students have a sense of what good quality work is, are able to compare their work to the quality standard, and know what to do to improve their work to bring it closer to the quality standard. We use this model in laboratory teaching, whereby students prepare for dedicated time in the laboratory that will be used for developing competency in techniques by watching exemplar materials, and then demonstrate their technique to a peer, who can review their work according to checklist criteria. Once the student is confident that their work is close to the required competency standard, they submit evidence for assessment, either by showing their approach to an assessor or uploading a video of them completing a technique for assessment.[7b, 7c, 21] This approach also aligns with the complex learning environment. For students to be able to draw together the various independent aspects that they need for a complex setting, they need to have capability in each of the individual aspects, so that they can effectively address the complexity – the act of brining all the component together to apply them to a new situation.

4. Consideration of learners’ emotions, motivations, and expectations is imperative in laboratory settings.

As described above, a lot of the work on pre-laboratory activities indicated unforeseen benefits in improving students’ confidence, motivation, and interest in the laboratory. In addition, laboratory activities are often contextualised in some real world setting to enhance their interest with students. Despite the acknowledged importance of considering affective dimensions of student learning, comparatively little research has been conducted on this aspect of laboratory learning. Some very useful work by Bretz has incorporated the concept of meaningful learning.[8] This relates to the principles of constructivism, an educational framework that describes the process of learning whereby students continually consider their understanding and models of the world (and chemical concepts) by seeing how new information that is presented relates and builds on that world view. The concept of meaningful learning adds the dimension of considering that students must have some interest and motivation in engaging with new information and experiences if they are to use it to challenge and extend their understanding of chemical concepts. This work has demonstrated that laboratory experiences that give students the sense of control lead to students having an understanding what they are doing, and developing a responsibility for their work. Within the context of the complex learning environment, students should be supported through points of difficulty or frustration – exactly at the point at which they experience complexity, guided by an understanding these frustration points are points where meaningful learning may occur. In practice this may mean an honest dialogue with students about where they may expect difficulties, and that it is intentionally designed as such. While we can highlight the importance of affective aspects of learning in the laboratory, much more research needs to be done in this area.

Applying the framework in practice

We turn our attention now to a consideration of how these overarching principles may be applied in practice. The purpose here is not to prescribe a set of experiments or recommend particular individual teaching approaches, but rather offer a case study as to how the laboratory literature might be utilised by readers considering their own laboratory curriculum.

At our institution, we are interested in the developing our laboratory curriculum so that it achieves the first of the stated goals mentioned above - to teach learners how to 'do' science. We designed a model whereby we could align laboratory activities to particular outcomes we wished to emphasise at particular stages of the curriculum (Figure 2), with the ultimate goal of being competent in experimental design. In our particular case, students study chemistry over five years, so we divided the stages into five; those with shorter or longer programmes may wish to adapt accordingly.

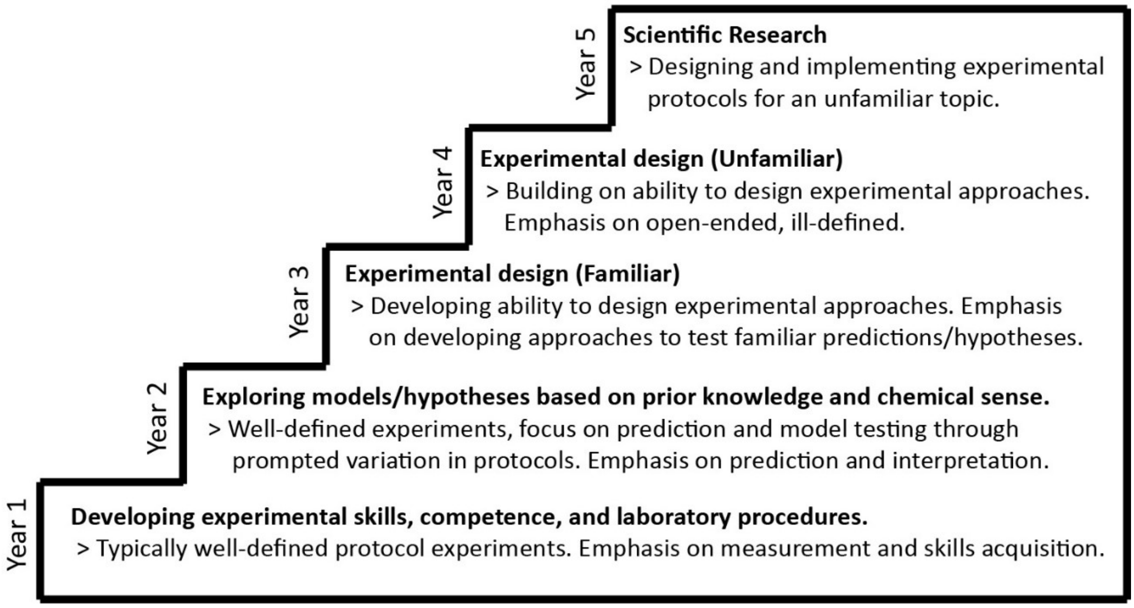

Figure 2. A curriculum model for developing experimental design, with focus of each stage highlighted

This curriculum model aims to incorporate the tenets of complex learning whereby each stage of the curriculum is one iteration more difficult, until the final point where students are tasked with designing and implementing protocols for an unfamiliar topic, in their final year project. Each stage (where a stage is a year in our arrangement) introduces a new level of complexity as well as continuing what was developed in previous years.

Stage 1

The first stage in this model focusses on the development of experimental skills and becoming comfortable and competent in the laboratory environment. The emphasis on skills and competencies rather than chemistry requires a different form of assessment. Assessment of laboratory skills is still unusual, but there are several examples in the chemistry education literature. These include in-situ demonstrations where students record their demonstration as a video on a mobile phone,[7c, 21-22] have assessment stations where students demonstrate their skills under assessment conditions,[17-18] and practical exams.[23] In our case, we modified the example where students demonstrate techniques while being recorded on their mobile phone to incorporate a peer-formative assessed component.[7b] Other types of experiments at this stage are around developing experimental competencies such as judgement, and examples of this type of activity are those which ask students to make a decision, or to perform some basic level of consideration about experimental procedure. For example, in an entry level inquiry experiment, students are required to design their work-up procedure in a highly structured activity.[24]

Stage 2

As students' confidence and competence in laboratory work grows, some additional complexity regarding thinking about model building can be introduced. These can often be modified from typical expository-type experiments found in the literature. For example, rather than simply asking students to follow procedures and observe what happens, incorporating "predict" and "explain" components into the instruction introduces students to the modelling process. An example in our case is the modification of the typical micelle experiment[25] to include a question posed to students to predict what will happen when the ionic strength of the solution increases. Students can discuss their prediction and complete the experiment (by studying micelles in increasing concentrations of saline solution) and then explain the results based on the model presented. A literature example of predict-observe-explain approaches outlines how this approach can be implemented in practice.[26] They are a convenient approach in transforming typical recipe experiments into those that align with the curriculum requirements at this stage. One common issue in laboratory education is that students do not "get the right answer", leaving an impression of personal incompetence, whereas often it is systematic (e.g. depends on equipment available). A way to avoid this is to instead ask students to compare values obtained within an experiment. We have modified typical vapour pressure experiments,[27] for example, so that instead of asking students to determine the vapour pressure of a liquid and compare it to the literature, we ask them to hypothesis what difference they expect between the liquids, and perform an experiment to see if their hypothesis is borne out.

Stage 3

In the next stage, we begin to emphasise experimental design. Within the description of the complex learning framework, experimental design is in itself a level of complexity, and thus needs careful guidance. We utilise a two-phase approach, whereby students first complete a traditional experiment to familiarise with experimental techniques, types of data, etc, and then follow this on with an inquiry, using the techniques and similar chemistry to that in the first part. This second part then adds in the additional complexity of experimental design.[28] This model is based on the divergent approach advocated by Kirschner[5a] and is also described by Tsaparlis for physical chemistry.[29] In addition, there are several examples of structuring a laboratory course so that the students ability to apply known techniques to new situations in a familiar experimental design approach. A typical example is this report on a multi-week approach for early undergraduate analytical chemistry.[30]

Stage 4 and 5

At Stage 4, the expectations of students are much greater and we now require them to consider experimental design in unfamiliar situations. At this stage, we conduct investigations in groups, so as to maximise peer support, as, in our observations, these tasks are quite difficult for students. Much of the traditional problem-based learning literature for laboratory work is appropriate here, with these activities often called “mini-projects”. Examples include activities for analytical chemistry,[31] spectroscopy,[32] organic chemistry,[33] inorganic chemistry,[34] drug discovery,[35] and chemical engineering.[36]

Stage 5 continues this work – indeed it is becoming increasingly common for students to conduct their research experience in groups. However more traditionally stage 5 involves students immersing in research groups. The intention is that the preparation that they have had from their curriculum to date means they can quickly and meaningfully integrate into the research environment.

Concluding Remarks

Designing new laboratory activities is not an easy task, and there are many design considerations that need to be taken into account. The purpose of this work is to illustrate some key considerations and give some basis from the literature on laboratory education for particular design decisions we advocate. The underlying principle is that within a complex learning framework, students’ progress through the curriculum should be considered with the explicit monitoring of what is additional at each stage, so that the desired outcomes that are new to each stage are supported by students’ prior experiences in their laboratory work. Examples from the literature are used to illustrate how the literature may be useful in sourcing and modifying experiments in the design of each curriculum unique to any institution. We believe that an explicit consideration of this curriculum design, and the progress of students through it, will lead to better outcomes regarding students ability to work in the chemistry laboratory.

References

1. Johnstone, A. H.; Wham, A., The demands of practical work. *Education in Chemistry* **1982,** *19* (3), 71-73.
2. Hofstein, A.; Lunetta, V. N., The laboratory in science education: Foundations for the twenty-first century. *Science Education* **2004,** *88* (1), 28-54.
3. (a) DeKorver, B. K.; Towns, M. H., General Chemistry Students’ Goals for Chemistry Laboratory Coursework. *Journal of Chemical Education* **2015,** *92* (12), 2031-2037; (b) DeKorver, B. K.; Towns, M. H., Upper-level undergraduate chemistry students’ goals for their laboratory coursework. *Journal of Research in Science Teaching* **2016,** *53* (8), 1198-1215.
4. (a) Domin, D. S., A review of laboratory instruction styles. *J. Chem. Educ* **1999,** *76* (4), 543-547; (b) Fay, M. E.; Grove, N. P.; Towns, M. H.; Bretz, S. L., A rubric to characterize inquiry in the undergraduate chemistry laboratory. *Chemistry Education Research and Practice* **2007,** *8* (2), 212-219; (c) Xu, H.; Talanquer, V., Effect of the level of inquiry of lab experiments on general chemistry students’ written reflections. *Journal of Chemical Education* **2012,** *90* (1), 21-28.
5. (a) Kirschner, P. A., Epistemology, practical work and academic skills in science education. *Science & Education* **1992,** *1* (3), 273-299; (b) Kirschner, P. A.; Meester, M. A. M., The laboratory in higher science education: Problems, premises and objectives. *Higher Education* **1988,** *17* (1), 81-98; (c) Anderson, R. O., *The experience of science: A new perspective for laboratory teaching*. Teachers College Press, Columbia University: New York, 1976; (d) Woolnough, B. E.; Allsop, T., *Practical work in science*. Cambridge University Press: Cambridge, 1985.
6. Agustian, H. Y.; Seery, M. K., Reasserting the role of pre-laboratory activities in chemistry education: a proposed framework for their design. *Chemistry Education Research and Practice* **2017,** *18* (4), 518-532.
7. (a) DeMeo, S., Teaching chemical technique. A review of the literature. *Journal of Chemical Education* **2001,** *78* (3), 373; (b) Seery, M. K.; Agustian, H. Y.; Doidge, E. D.; Kucharski, M. M.; O'Connor, H. M.; Price, A., Developing laboratory skills by incorporating peer-review and digital

badges. *Chemistry Education Research and Practice* **2017,** *18*, 403-419; (c) Hensiek, S.; DeKorver, B. K.; Harwood, C. J.; Fish, J.; O'Shea, K.; Towns, M., Improving and Assessing Student Hands-On Laboratory Skills through Digital Badging. *Journal of Chemical Education* **2016,** *93* (11), 1847-1854.

8. Galloway, K. R.; Malakpa, Z.; Bretz, S. L., Investigating affective experiences in the undergraduate chemistry laboratory: Students' perceptions of control and responsibility. *Journal of Chemical Education* **2016,** *93* (2), 227-238.

9. Singer, S. R.; Nielsen, N. R.; Schweingruber, H. A., Discipline based education research. *Washington, DC: The National Academies* **2012**.

10. van Merriënboer, J. J. G.; Kirschner, P. A.; Kester, L., Taking the load off a learner's mind: Instructional design for complex learning. *Educational Psychologist* **2003,** *38* (1), 5-13.

11. Tamir, P. *The role of the laboratory in science teaching*; University of Iowa: Iowa, 1976.

12. Carnduff, J.; Reid, N., *Enhancing undergraduate chemistry laboratories: pre-laboratory and post-laboratory exercises*. Royal Society of Chemistry: 2003.

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

14. (a) Schmidt-McCormack, J. A.; Muniz, M. N.; Keuter, E. C.; Shaw, S. K.; Cole, R. S., Design and Implementation of Instructional Videos for Upper-Division Undergraduate Laboratory Courses *Chemistry Education Research and Practice* **2017,** *18*, 749-762; (b) Winberg, T. M.; Berg, C. A. R., Students' cognitive focus during a chemistry laboratory exercise: Effects of a computer-simulated prelab. *Journal of Research in Science Teaching* **2007,** *44* (8), 1108-1133.

15. Johnstone, A. H.; Sleet, R. J.; Vianna, J. F., An information processing model of learning: Its application to an undergraduate laboratory course in chemistry. *Studies in Higher Education* **1994,** *19* (1), 77-87.

16. DeMeo, S., Teaching Chemical Technique. A Review of the Literature. *Journal of Chemical Education* **2001,** *78* (3), 373-379.

17. Chen, H.-J.; She, J.-L.; Chou, C.-C.; Tsai, Y.-M.; Chiu, M.-H., Development and Application of a Scoring Rubric for Evaluating Students' Experimental Skills in Organic Chemistry: An Instructional Guide for Teaching Assistants. *Journal of Chemical Education* **2013,** *90* (10), 1296-1302.

18. Kirton, S. B.; Al-Ahmad, A.; Fergus, S., Using Structured Chemistry Examinations (SChemEs) As an Assessment Method To Improve Undergraduate Students' Generic, Practical, and Laboratory-Based Skills. *Journal of Chemical Education* **2014,** *91* (5), 648-654.

19. Hendry, G., Integrating feedback with classroom teaching. In *Reconceptualising Feedback in Higher Education: Developing Dialogue with Students*, Merry, S.; Price, M.; Carless, D.; Taras., M., Eds. Routledge: 2013; pp 133-134.

20. Sadler, D. R., Formative assessment and the design of instructional systems. *Instructional Science* **1989,** *18* (2), 119-144.

21. Towns, M.; Harwood, C. J.; Robertshaw, M. B.; Fish, J.; O'Shea, K., The Digital Pipetting Badge: A Method To Improve Student Hands-On Laboratory Skills. *Journal of Chemical Education* **2015,** *92* (12), 2038-2044.

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

23. Neeland, E. G., A One-Hour Practical Lab Exam for Organic Chemistry. *Journal of Chemical Education* **2007,** *84* (9), 1453.

24. Mistry, N.; Fitzpatrick, C.; Gorman, S., Design Your Own Workup: A Guided-Inquiry Experiment for Introductory Organic Laboratory Courses. *Journal of Chemical Education* **2016,** *93* (6), 1091-1095.

25. Marcolongo, J. P.; Mirenda, M., Thermodynamics of sodium dodecyl sulfate (SDS) micellization: an undergraduate laboratory experiment. *Journal of Chemical Education* **2011,** *88* (5), 629-633.

26. Smith, K. C.; Edionwe, E.; Michel, B., Conductimetric Titrations: A Predict− Observe− Explain Activity for General Chemistry. *Journal of chemical education* **2010,** *87* (11), 1217-1221.
27. Chen, W.; Haslam, A. J.; Macey, A.; Shah, U. V.; Brechtelsbauer, C., Measuring Vapor Pressure with an Isoteniscope: A Hands-On Introduction to Thermodynamic Concepts. *Journal of Chemical Education* **2016,** *93* (5), 920-926.
28. Seery, M. K.; Kew, W.; Jones, A. B.; Mein, T., Unfinished recipes: structuring upper division laboratory work to scaffold experimental design skills. *Journal of Chemical Education* **Accepted**.
29. Tsaparlis, G.; Gorezi, M., Addition of a project-based component to a conventional expository physical chemistry laboratory. *Journal of Chemical Education* **2007,** *84* (4), 668.
30. Cessna, S. G.; Kishbaugh, T. L.; Neufeld, D. G.; Cessna, G. A., A Multiweek, Problem-Based Laboratory Project Using Phytoremediation To Remove Copper from Soil. General Chemistry Labs for Teaching Thermodynamics and Equilibrium. *Journal of chemical education* **2009,** *86* (6), 726.
31. Kerr, M. A.; Yan, F., Incorporating course-based undergraduate research experiences into analytical chemistry laboratory curricula. *Journal of Chemical Education* **2016,** *93* (4), 658-662.
32. McDonnell, C.; O'Connor, C.; Seery, M. K., Developing practical chemistry skills by means of student-driven problem based learning mini-projects. *Chemistry Education Research and Practice* **2007,** *8* (2), 130-139.
33. (a) Oliveira, D. G.; Rosa, C. H.; Vargas, B. P.; Rosa, D. S.; Silveira, M. r. V.; de Moura, N. F.; Rosa, G. R., Introducing undergraduates to research using a Suzuki–Miyaura cross-coupling organic chemistry miniproject. *Journal of Chemical Education* **2015,** *92* (7), 1217-1220; (b) Ong, J.-Y.; Chan, S.-C.; Hoang, T.-G., Empowering Students To Design and Evaluate Synthesis Procedures: A Sonogashira Coupling Project for Advanced Teaching Lab. *Journal of Chemical Education* **2018**.
34. (a) Coe, B. J., Syntheses and Characterization of Ruthenium (II) Tetrakis (Pyridine) Complexes. An Advanced Coordination Chemistry Experiment or Mini-Project. *Journal of chemical education* **2004,** *81* (5), 718; (b) Schaeffer, C. D.; Myers, L. K.; Coley, S. M.; Otter, J. C.; Yoder, C. H., Preparation, analysis, and reactivity of bis [N, N-bis (trimethylsilyl) amino] tin (II): An advanced undergraduate laboratory project in organometallic synthesis. *Journal of Chemical Education* **1990,** *67* (4), 347.
35. Fray, M. J.; Macdonald, S. J.; Baldwin, I. R.; Barton, N.; Brown, J.; Campbell, I. B.; Churcher, I.; Coe, D. M.; Cooper, A. W.; Craven, A. P., A practical drug discovery project at the undergraduate level. *Drug discovery today* **2013,** *18* (23-24), 1158-1172.
36. Cancela, A.; Maceiras, R.; Sánchez, A.; Izquierdo, M.; Urréjola, S., Use of learning miniprojects in a chemistry laboratory for engineering. *European Journal of Engineering Education* **2016,** *41* (1), 23-33.