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Teaching Chemistry in Higher Education

A Festschrift in Honour of Professor Tina Overton

Edited by

Michael K. Seery and Claire Mc Donnell

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Developing student expertise in scientific inquiry

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The role of developing student expertise in scientific inquiry often falls on laboratory work. Domin's taxonomy of laboratory instruction styles has been expanded with more detailed scrutiny of inquiry instruction. The most common form of laboratory teaching is the confirmation style where students follow recipes to reproduce known results in a straight-forward and resource-efficient manner. This style achieves few pedagogic goals of laboratory education and inquiry-based instruction is better suited to the acquisition of the skills, methodology, and procedures of scientific inquiry.

A guided inquiry instruction style improves on the confirmation style by reinforcing the point of the experimental work, even though students will still to follow-the-recipe where they can. Tutor support is needed when students apply what they know about the scientific method to an experiment design task. In the absence of support, students are unable to engage in scientific inquiry. With extensive support even novices can design and carry out good experiment work. Advice for and examples of the implementation of inquiry are provided to help the reader do this in their own teaching.

Influence of Professor Tina Overton

Professor Tina Overton has been a hugely significant influence on all of my teaching fellow life. I have drawn much inspiration from her work on problem-based learning (Overton, 2001; 2007) and the findings about the usefulness of different aspects of a chemistry degree course (Hanson and Overton, 2010). She was the leader of the first workshop on educational research I attended, and she is an inspiration and a role model for all chemistry teaching specialists, not least Yorkshire-based female university teachers like me.

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Introduction

The role of developing chemistry students' inquiry skills usually finds a place as part of the laboratory curriculum. Laboratory work is considered to be a central component of studying chemistry. It can serve many purposes including illustrating concepts and phenomena, teaching experimental skills, and developing expertise in inquiry (Kirschner, 1992; Hofstein and Lunetta, 2004; Reid and Shah, 2007). Historically, laboratory teaching involved an investigative approach giving experience of systematic research (Hofstein and Lunetta, 1982; Reid and Shah, 2007) mirroring the apprenticeship served by a PhD student training to be an experimental scientist (Stewart and Lagowski, 2003). In more recent years, the emphasis in laboratory teaching has been put on the chemistry being performed (Meester and Maskill, 1995, quoted in Reid and Shah, 2007).

Classification of laboratory activities

Different authors have used the same terms to describe very different laboratory activities. Domin's (1999) taxonomy of laboratory teaching styles (Table 1) provides some clarity through a classification of activities based on approach, procedure, and outcome. Fay *et al.* (2007) and Buck *et al.* (2008) have added to this by breaking down the inquiry domain into different levels of inquiry (Table 2). There is some overlap between the two classifications: Domin's expository style matches the confirmation style (inquiry level 0), and his inquiry style encompasses structured to authentic inquiry (inquiry levels 1–3). The discovery style can also be thought of as guided inquiry (inquiry level 1) because the classification in Table 2 does not consider whether the outcome has been predetermined or not. Authentic inquiry, inquiry level 3 is seen in scientific research where theory is used to develop experiments that allow development of new theory. This chapter uses the descriptive terms from Tables 1 and 2 to describe different laboratory activities.

Table 1: Taxonomy of laboratory instruction styles (Domin, 1999)

	Outcome	Approach	Procedure
Expository	Predetermined	Deductive [†]	Given
Inquiry	Unknown	Inductive [‡]	Student generated
Discovery	Predetermined	Inductive	Given
Problem-based	Predetermined	Deductive	Student generated

[†]Deductive approach: students use specific examples of a phenomenon to illustrate an underlying principle.

[‡]Inductive approach: students develop an understanding of an underlying principle by studying a specific example of a phenomenon.

Table 2: A classification of experiment by level and type of inquiry (Fay *et al.*, 2007; Buck *et al.*, 2008) based on what is (☑) and is not (☒) provided to students

Level	Problem/question	Theory/background	Procedure/design	Analysis Protocol	Communication format	Conclusions
0: Confirmation	☑	☑	☑	☑	☑	☑
1: Structured Inquiry	☑	☑	☑	☑	☒	☒
1: Guided Inquiry	☑	☑	☑	☒	☒	☒
2: Open Inquiry	☑	☑	☒	☒	☒	☒
3: Authentic Inquiry	☒	☒	☒	☒	☒	☒

The confirmation instruction style

The confirmation or expository instruction style, inquiry level 0, is also called verification, recipe-following, or cook-book work. These terms describe activities where students follow detailed instructions to practice laboratory techniques and reproduce theoretical phenomena taught in lectures. The confirmation style presents the laboratory as being subservient to theory and science as “a body of information which is (and can be) verified and certain” (Kirschner, 1992). In confirmation laboratories, students are typically not given the opportunity to develop expertise in scientific inquiry. Criticisms of the confirmation style are not new (e.g. Wham, 1977) and almost all papers written about this style highlight its flaws. The published criticisms include the following:

- Scientific inquiry is a complex procedure and the principles of the scientific method cannot be learned “by osmosis”; students need to be taught how it is done (Garratt and Tomlinson, 2001);
- Applying set algorithms to solve problems is not really problem solving (Bodner, 2003);
- “Critical, independent, creative thinking is rarely expected or encouraged” or possible (Stewart and Lagowski, 2003);
- Students learn to ask “what is the answer supposed to be?” rather than “what is the answer?” (Allen *et al.*, 1986);
- This type of practical often leads to “boredom and apathy towards scientific work” (Kirschner, 1992);
- Exercises can be performed with little preparation and engagement by students (Domin, 1999; 2007);
- The goals the students have for their laboratory work (finishing early, avoiding mistakes) are different to the pedagogic aims and intended learning outcomes of the work (DeKorver and Towns, 2015) hence these are not achieved (Hofstein and Lunetta, 2004; Abraham, 2011);
- Students do the majority of their learning after the practical session when they set about completing post-laboratory assignments (Domin, 2007).

To sum up, confirmation exercises require low levels of cognitive engagement. Students are not involved in experiment planning or design so the laboratory is an unrealistic portrayal of scientific inquiry. There are low levels of student engagement, and little creative, critical or independent thinking is required. Relatively little learning occurs, because students spend their time determining whether they have the correct answer instead of thinking more deeply about what they are doing. The work lacks relevance to real life. Nonetheless, the confirmation style of laboratory teaching persists.

Some educators have pragmatic reasons for adopting the confirmation instruction style which are rooted in predictability. Where a procedure and outcome is known in advance, the practical exercise is easy to plan for and can make the most of available resources. Inquiry-style work is inherently less predictable and activities can be limited by the availability of equipment or chemicals (Seery *et al.*, 2019; Tsaparlis and Gorezi, 2007). Inquiry-style work also needs greater teaching support compared to confirmation instruction (between 2–10 students per instructor (Tsaparlis and Gorezi, 2007; Keller and Kendal, 2017) compared to 40 students per class (Cheung, 2011)). These factors can make large enough barriers to implementation to dissuade teachers from inquiry laboratories (Cheung, 2011).

Some educators have pedagogic reasons for adopting the confirmation style. These are rooted in a philosophy of teaching that considers the purpose of practical work is to illustrate chemistry learned in class; that practical work should be subservient to learning scientific theory. Students learn less factual (chemistry) knowledge when given tasks at higher levels of inquiry (Xu and Talanquer, 2013). The high level of cognitive load required by novices operating at higher levels of inquiry impedes learning of

concepts and they can struggle to apply knowledge outside of the context of the inquiry or problem (Kirschner *et al.*, 2006).

Educators acknowledging the flaws in the confirmation style have tried different strategies to improve on it. One approach is to use social interaction to enhance learning in laboratories, by embedding questions in the laboratory instructions (Cox and Junkin, 2002) or using an argument-driven inquiry (ADI) instructional model involving critique and peer-feedback of data-interpretation (Walker *et al.*, 2011). Another approach is to reduce the high cognitive load associated with laboratory work (Johnstone *et al.*, 1994; Kirschner *et al.*, 2006; Reid and Shah, 2007; Reid, 2008) for example through carefully planned prelaboratory tasks (see Agustian and Seery, 2017, for a review), dedicated skills enhancement sessions (Sedwick *et al.*, 2018), or experimental seminars for discussion, comparison, reasoning and modelling of results (Kirschner, 1992). Recontextualising knowledge where a subject is deeply fragmented is difficult (Luckett, 2009) and reducing the cognitive load associated with recontextualisation can be achieved when each exercise is presented in the same way (cf. Hall and Vardar-Ulu, 2013). However, reducing the cognitive load does not prevent a typical student reverting to recipe-following where it is the quickest way of completing set tasks (DeKorver and Towns, 2015).

Alternatives to the confirmation instruction style

The nature of the activities, the expectations of those involved, and the nature of the assessment all impact on the learning environment in the laboratory (Hofstein and Lunetta, 2004) and learning a process like the scientific method is best done through practice (Abraham, 2011). “*To change the experience, you don’t need to change the experiment, just what you do with it*” (quoted in Reid and Shah, 2007). For example, confirmation exercises can be reworked as problem-based or guided inquiry tasks (see for example McGarvey, 2004; Allen *et al.*, 1986; Mohrig *et al.*, 2007). Problem-based learning (PBL) is a subset of context-based learning in which learning occurs through the solving of a problem (Smith, 2012; Overton, 2007). Students plan an experiment in order to solve the problem and learn about an aspect of the experiment (McGarvey, 2004) and they engage better in PBL mini-projects than in confirmation laboratory classes (McDonnell *et al.*, 2007). As noted above, downside to this style is that the learning can be so entwined with the context or problem that students struggle to apply the ideas in a different context (Kirschner *et al.*, 2006).

Inquiry-based learning provides opportunities for students to engage meaningfully in scientific investigation (Hofstein and Lunetta, 2004). Students can “discover” and explore a phenomenon for themselves through laboratory work (Albright and Beussman, 2017; Bodner *et al.*, 1998; Kulevich *et al.*, 2014) with lectures on principles occurring afterwards (Abraham, 2011; Allen *et al.*, 1986). Resources are easier to plan for where procedures are given or predictable (Seery *et al.*, 2019) such as in lower levels of inquiry work. These exercises have better student outcomes and better student feedback than confirmation exercises (see for example Chatterjee *et al.*, 2009; Sedwick *et al.*, 2018). Spreading the inquiry over several weeks allows time for risk assessment and chemical and equipment purchase enabling students to engage in authentic inquiry (Quattrucci, 2018).

Scaffolding the stages of inquiry guides students through unfamiliar processes, reducing cognitive load, helping students perform better (Morgan and Brooks, 2012), and enabling them to engage in inquiry work (Quattrucci, 2018). Scaffolding is important because switching from confirmation exercises to inquiry work can be difficult for students (Hall and Vardar-Ulu, 2013; Bruck and Towns, 2009). Examples of scaffolding include thoughtfully-designed simulations that guide student inquiry of a concept (Moore *et al.*, 2013), and a prerequisite experiment design module for an inquiry laboratory module (Iimoto and Frederick, 2011).

Methods

The university where I work has a strong research identity which shapes its teaching. The expectation is that students will end their third year laboratory modules “research-ready” and equipped to undertake a masters-level research project. In the first and second year, students on all chemistry degree programmes follow a programme of confirmation exercises with little in the way of open-ended experiments. They complete a set of exercises in inorganic, organic, or physical chemistry laboratories, before rotating onto the next. There are typically 50 students in the laboratory with one academic and two or three postgraduate laboratory teachers as well as a technician. This work is set in the second year inorganic chemistry laboratory where students spend five weeks before moving on.

My aim is to develop students’ inquiry skills so that they are ready for open-ended experimentation and research work in their final year. A curriculum is made up of three distinct components: knowledge, skills, and subject-related attributes (Barnett, 2009; Barnett *et al.*, 2001). I used this as a lens to analyse my laboratory curriculum and found that the emphasis fell strongly on chemistry knowledge. The majority of exercises allowed students to follow recipes without much thought. The skills and attributes students were developing focussed on survival and finishing the work in the allotted time rather than those desirable in a chemist. My laboratory course was, therefore, not helping students become “research-ready”.

My work has looked at building inquiry into the teaching laboratory within and alongside the existing confirmation style of instruction, without large cost implications. My first attempts tried experiments with unknown outcomes. Students were given written instructions but no extra support. The work they produced showed they were unable to experiment instead they were anticipating a correct answer and had not engaged with the inquiry. Hall and Vardar-Ulu (2013) noted this too and Bruck and Towns (2009) highlight the difficulty students have in changing from confirmation to inquiry work. This chapter describes observations from two subsequent attempts. A third attempt introducing open inquiry is described in detail in Burnham (2013). These studies were granted ethical approval in accordance with institution guidelines.

Presentation and Discussion of Findings

Reworking confirmation exercises as guided inquiry

The first step in introducing inquiry was to rework the confirmation exercises as structured/guided inquiry exercises. The exercises were structured around a research aim or question to set a scientific tone to the work (see Table 4 for an example). The post-laboratory assignments focused on addressing the aim/question and asked for further work suggestions on how to continue. Questions were added at points in the experimental instructions so that students would think about the chemistry they were doing. Postgraduate laboratory teachers were tasked with engaging each student in a discussion about the chemistry at least once during the laboratory session. The changes also included consideration of the cognitive load of laboratory work. New pre-laboratory assignments focussed on the experiment procedure and only included questions about theory required to understand it. Each exercise had the same structure to minimise the cognitive load associated with unfamiliar layout. Finally, activities that were superfluous to the research aim or question were removed to give students time to stop, think, and reflect whilst doing their work during the laboratory class. It was hoped that the guided inquiry style of these laboratory classes would model the scientific method and turn students into better experimenters. Evidence from different sources was analysed in a hermeneutic spiral in order to form a description of the student experience in the laboratory (Bodner, 2004; Shane, 2007). This showed that students did the

Table 3: Interventions introduced to develop student expertise in inquiry
 (* highlights approaches discussed in this chapter)

Intervention	Description
Investigation into the products of a reaction	Interpretation of the outcome of the acetylation of ferrocene using spectroscopic data, written up as a report to allow for the unpredictable distribution of reaction products
Investigation into the products of a reaction	Interpretation of the outcome of the acetylation of ferrocene using spectroscopic data, written up as a report to allow for the unpredictable distribution of reaction products
Reworking confirmation exercises as guided inquiry (Student Experience project)*	A common structure given to each exercise. Addition of a chemical research aim/question. New prelaboratory activities focusing on experiment protocol. Addition of inlaboratory discussion prompted by questions in the method and postgraduate laboratory teachers. Postlaboratory assignment using the data from the laboratory to answer research aim/question. Superfluous activities removed to free up time for thinking and reflection
Introducing experiment design exercises (Kitchen Project, Be Creative Lab)*	Self-study task to learn about the scientific method before designing a scientific investigation
An open inquiry experiment	Students presented with the symptoms of an issue with a procedure and asked to design an investigation into the origin of the issue. Additional experiment design workshop and extra facilitation provided during experimental work (for details see Burnham, 2013)

required tasks. The pre-laboratory assignment focus was confirmed as being on the laboratory work rather than the underlying chemistry. In the laboratory, students talked to each other about what they were doing and they also asked the postgraduate laboratory teachers for help with the tasks. Students thought about the chemistry when prompted by the questions in the text or discussion with postgraduates, and postgraduates helped the students understand the chemistry they were doing. The post-laboratory assignment helped students understand what they had done. When posed with the question “*To what extent do you understand the investigation having done the prelaboratory, the laboratory, and the postlab?*”, 21% of respondents replied completely, 53% quite a lot and 26% somewhat or not really.

The aim or research question highlighted to students the point of what they were doing and the majority understood the investigation by the end of the postlaboratory. Similarly to the confirmation exercises investigated by Domin (2007), the post-laboratory assignment helped the students understand what they had done. Including in-text questions and in-laboratory discussion helped the students understand what they were doing just as in the findings of Cox and Junkin (2002) and the question driven pedagogy of Teixeira *et al.*, (2010). Students generally understood the point of what they were doing with respect to the aim of the work, but their understanding was less outside of set tasks. Some students were interested in the chemistry they were doing whereas others were satisfied with cutting corners providing they completed the required activities. Learning was therefore prompted by the required activities, and despite the intent for students to engage in inquiry in the laboratory, the evidence suggested students were doing the laboratory rather than engaging with it.

A strong theme was that they found these laboratory classes stressful. The stress was linked to the need to complete set tasks within a given time frame. Students highlighted irritating behaviours in others that impeded their progress in the laboratory and they felt under pressure when doing write-ups. This stress was present even though, on average, 90% of students finished and left the laboratory before the end of the allotted time. The student researcher suggested that finishing early was viewed as luck, not as a reward for being efficient. Postgraduates who had done the previous course noted a more relaxed atmosphere in the reworked sessions, however, the extra time to complete the activities appeared to have gone unnoticed by the students.

The focus on an aim or research question was successful in imparting to students an awareness of the chemical purpose of each exercise, but students in the reworked guided inquiry laboratory were still recipe-following. This is unsurprising since DeKorver and Towns (2015) highlight that students will adopt the most straightforward approach in the laboratory. Students wanted feedback that explains where marks were lost, suggesting they were more concerned with individual assessments than the inquiry theme of the course.

Table 4: The guided inquiry scaffolding used in an experiment by Armstrong *et al.* (2017)

Guided inquiry component	Example
Research aim/question	Determine the structure of $[\text{RuH}_2(\text{CO})(\text{PPh}_3)_3]$ using IR and NMR spectroscopies.
Question in the experimental instructions	What is the purpose of the fourth equivalent of PPh_3 in the reaction?
Questions scaffolding the interpretation and discussion of results	Comment on the purity of your $[\text{RuH}_2(\text{CO})(\text{PPh}_3)_3]$ using your IR and NMR spectra as evidence.
Conclusion and further work suggestion	In three sentences, write a brief conclusion. Include what you learned from your spectra, the structure you deduced and to what extent you were able to achieve the research aim. Suggest a change that could be made to the dihydride complex that would move either the $\nu(\text{MH})$ or the $\nu(\text{CO})$ in the IR spectrum in order to tell definitively which peak was which.

Introducing experiment design exercises

A second step in introducing inquiry into the undergraduate course was to introduce experiment design exercises where students learned about the scientific method prior to designing an investigation. Smith (2012) ascribes the passive nature of student learning in the laboratory to a lack of experiment planning and Hanson and Overton's (2010) report showed that recent graduates would have liked to have done more experimental design during their degree course. Two interventions were trialled; the Kitchen Project and the Be Creative Laboratory (BCL). In the Kitchen Project, students were asked to learn about the scientific method before attending a tutor-led discussion of it. After the discussion, they designed, executed, and reported on an investigation done in their kitchens (similar to Jones, 2011). In the BCL, students were asked to learn about the scientific method and write a 500 word summary about it. They then attended a workshop in which they designed an investigation or experiment based on a real-life scenario; finding a use for fruit waste, designing a synthesis of a DMSO complex, investigating air-quality in Sheffield, and investigating the impact of dimethicone entering the sewage waste stream. Students were tasked with writing a hypothesis, designing experiments to test it, and writing a risk assessment for their proposed investigation.

The purpose of the preparatory scientific method tasks was to lead students into designing experiments without extra teaching. The research question “*what is the effectiveness of the scientific method task in planning and reporting an experiment?*” was used to design a simple evaluation of the interventions. Data from the Kitchen Project showed that all students had engaged with the scientific method task and subsequent small group discussion with a tutor. Data from the BCL indicated that students interpreted the scientific method task in different ways. There was no correlation between the amount of the scientific method task done and the quality of the Kitchen Project investigations. This suggests that the group discussion was useful in smoothing-out the differences between those who were very well prepared and those who had achieved less. The varied interpretations of the scientific method task in the BCL indicates that a tutor-facilitated discussion of the task is essential in ensuring all students have had the opportunity to meet the required learning outcomes before proceeding to an experiment design task.

Tutor assistance was found to be necessary to help students identify experiment variables in both the Kitchen Project and the BCL. Experiment designs were not uniform in quality. Although some showed awareness of the importance of repetition of measurements to get accurate and precise results, others were much less structured. Students in the Kitchen Project had completed the guided inquiry laboratory programme the year before, but their need for help showed that the guided inquiry programme and the scientific method task had not prepared them to be able to design an experiment unassisted. This agrees with the finding from Garratt and Tomlinson (2001) that experiment design needs to be taught.

In general, students who spent more time researching, preparing and planning their experiment did better quality investigations. These students had the same background as the students in my unsuccessful attempts to introduce inquiry, which shows that any student has the potential to do good quality experimental work if given the right support. The benefits of inquiry work can extend several years after the intervention (Szteinberg and Weaver, 2013). A Kitchen Project participant with prior experience of intensively-supported experiment design found that the scientific method task merely reinforced what they already knew.

The BCL students appreciated the opportunity of doing some experiment design. It is noteworthy that they wanted more experiment design, earlier in their degree course. This discrepancy may be the root of the wish of graduates that more experiment design had been included in their degree courses (Hanson and Overton, 2010).

Practical implications and adaptability

Scientific inquiry can be presented with different amounts of structure. Where resources are stretched, structured or guided inquiry scaffolding can be added to confirmation exercises to give them a sense of purpose. Tasking students to learn about the scientific method can feed into a class discussion of this before they set about designing and executing an experiment. Confirmation exercises can be transformed into open inquiry, problem-based inquiry, or authentic inquiry, where students set their own aims, design and realise an experiment, and analyse the resulting data.

When implementing inquiry in your context, you will need to strike a balance between the desired outcome and the resources available to you. If resources are limited and you would like students to work with purpose, you can rework confirmation laboratories with a structured or guided inquiry approach. If you wish students to learn to about the scientific method, you can combine research into the scientific method with facilitated discussion of this. Inquiry style instruction requires careful consideration of cognitive load

and suitable scaffolding of learning tasks to embed knowledge so that it can be applied outside of the inquiry context. There is a wealth of advice in the literature to be considered when implementing inquiry into the curriculum. Examples are given in Table 5 and you should consider the following when planning inquiry style instruction:

- Ensure the students have a good theoretical knowledge base before starting laboratory work (but not the answers their experiments will give, Bruck and Towns, 2009) and consider introducing new techniques separately in skills-based laboratory classes (Sedwick *et al.*, 2018) or training sessions (Ford *et al.*, 2008);
- Good facilitation is necessary because students who are familiar with one type of experiment will assume that all experiment work is the same unless they are made to see otherwise (Mohrig *et al.*, 2007);
- Help students develop reasonable expectations of the success (or lack of) of inquiry work (Bruck and Towns, 2009). Using errors arising from real-life experimental work provides excellent learning opportunities about dealing with poor data (Davis *et al.*, 2017);
- Tailor the scaffolding to the experience-level of the student because, although novice students benefit from strongly-guided learning activities, these can disadvantage more experienced students who have developed their own ways of doing things (Kirschner *et al.*, 2006);
- Ease students into inquiry by incrementally increasing the amount of freedom they are given (Bruck and Towns, 2009). Introduce a learning stage before the experience stage (Wham, 1977) so that students can perform a trial run on a model system before doing the actual experiment (Newton *et al.*, 2006);
- The experiment design process should be scaffolded and facilitated (Etkina *et al.*, 2010) and can be introduced outside of laboratory work (as with limoto and Frederick, 2011; Jones, 2011).

It is important to get buy-in to an inquiry-style of instruction from all participants; students, teaching assistants and staff. Students need to understand the purpose of the inquiry work they are being asked to do. They show a preference for a more structured level of inquiry if a topic is perceived to be difficult (Basey and Francis, 2011). They believe they learn more and get higher grades in guided inquiry than in open inquiry experiments (Chatterjee *et al.*, 2009) but they may benefit from activities that they have not liked (Sandi-Urena and co-workers, 2011). Basey and Francis (2011) noted that some teaching assistants facilitated an open inquiry laboratory in the manner of a guided inquiry laboratory. Professional development activities can assist teaching assistants to develop as facilitators rather than disseminators of knowledge (Wheeler *et al.*, 2017a; 2017b). Colleagues need convincing that barriers to implementation are not insurmountable (Cheung, 2011). Student-directed project work is accompanied by significant demands on chemical, equipment, and teaching resources (Keller and Kendall, 2017) which can be optimised where activities are predictable (Domin, 1999). However, changing even one activity can benefit students (Cacciatore and Sevian, 2009). In addition, changes increase engagement with laboratory work (Mc Donnell *et al.*, 2007) and the positive benefits extend for several years afterwards (Szteinberg and Weaver, 2013).

Conclusions

Research and scientific inquiry are often reserved until the late stages of a degree programme. However, these activities can be done by less experienced students, provided the research and inquiry processes are appropriately scaffolded. The extended benefits of inquiry work will benefit final year research because

Table 5: Examples of activities at different levels of inquiry (co-authors omitted for clarity)

Instruction style	Examples
0: Confirmation	Cacciatore (2009) – Parameters of recipe laboratory exercise compared with a problem-based inquiry exercise
1: Guided Inquiry	Albright (2017) – Example of a discovery (guided inquiry) exercise Allen (1986) – How to turn a verification experiment into a guided inquiry exercise Bodner (1998) – Results of integrating discovery laboratories into the curriculum Ford (2008) – Using a mentor to guide students through the research process Gaddis (2007) – Different ways of incorporating guided inquiry into the lab Hall (2013) – Careful structuring of activities and introduction of new skills week-by-week in a semester-long laboratory course MacKay (2014) – Hypothesis testing using the Wittig reaction Newton (2006) – Scaffolding a synthetic research project with a practice-run making a model compound Teixeira (2010) – Questions guiding interpretation of data and design of subsequent experiments
Problem-based learning	Mc Donnell (2007) – Multi-week group PBL projects McGarvey (2004) – Examples of PBL laboratory exercises where students design their own procedure to achieve certain experimental objectives Smith (2012) – Outlining how to use PBL laboratory work in place of recipes Torres King (2018) – A two week organic chemistry laboratory activity based on catalysis
2: Open Inquiry	Bertram (2014) – Multi-week group projects fostering research skills Burnham (2013) – Student-designed investigations based on teaching lab exercises Herrington (2011) – Inquiry-based experiment on specific heat capacity Martineau (2013) – Team-based experiment design and execution to achieve authentic science Mistry (2016) – Student-designed workup to separate organic molecules
3: Authentic Inquiry	Etkina (2010) – Scaffolded investigative science learning environment allowing students to develop scientific abilities as well as learning concepts Quattrucci (2018) – Students identify problems and write experiments in areas of chemistry of interest to them
Combination of approaches	Seery (2019) – Scripted exercises leading into student-driven [guided and open] inquiry work Walker (2011) – Argument driven inquiry. Open inquiry coupled with discussion and peer review sessions Wham (1977) – Scripted exercises leading into discovery project work

the student will be familiar with scientific inquiry and experiment design and will therefore be a more active contributor to their project. My results show the importance of good facilitation when students design an experiment of their own, therefore, investment in teaching resource must be made in order to realise learning outcomes associated with developing expertise as a researcher. The role of developing students' scientific inquiry skills does not need to be confined to the laboratory, but it is in the laboratory where the benefits will ultimately be felt.

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