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Commentary

Establishing the Laboratory as the Place to Learn How to Do Chemistry

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ABSTRACT: The laboratory occupies a central place in chemistry curricula, but the reported goals of laboratory work are very broad. This commentary considers the variety of reported goals of laboratory work and seeks to address the question of what the pedagogic goals for laboratory work are in our curriculum. Drawing on literature from chemistry education research, history of science, and epistemology of laboratory work, it advocates seeking a single, well-defined goal of laboratory work as the place *to learn how to do chemistry*.

KEYWORDS: *First-Year Undergraduate/General, Second-Year Undergraduate, Upper-Division Undergraduate, Laboratory Instruction, Curriculum, Hands-On Learning/Manipulatives, Learning Theories*

■ INTRODUCTION

The recent editorial[1] by Bretz in this *Journal* calling for more research on laboratory learning in chemistry education is very welcome reading. Proposing the removal of laboratory work from the curriculum will likely result in a visceral reaction from most chemists and chemistry educators, who will express a sense that laboratory experience is an innate part of being a chemist. This sense of identity of the laboratory in the chemist's experience is partly due to history, with laboratory work being considered a core part of a chemistry curriculum since von Liebig began in the 1830s shifting from the model of lecture with demonstrations to one that included a laboratory program that emphasized the development of laboratory skills and approaches to science,[2,3] a model that quickly spread to other leading schools.[4,5] This notion of identity is elegantly expressed by Chang, who discerns chemists from physicists by writing about chemists as *makers*, concluding that the inclusion of a laboratory environment is an implicit part of a chemist's identity.[6] This innateness is reflected in guidelines for accrediting chemistry degree programmes. The American Chemical Society Committee on Professional Training requires bachelor degrees to have 400 h of laboratory experience beyond introductory chemistry[7] while the Royal Society of Chemistry requires bachelor and undergraduate master degrees to have 300 and 400 h of laboratory experience, respectively, as well as an undergraduate research project.[8] However, as Bretz's editorial indicates, there is likely to be increasing demand for a case to be made for the role of laboratory learning, especially given the consequent resource costs for inclusion of laboratory work in in the curriculum. Therefore, more research demonstrating the nature and scope of learning in the chemistry laboratory will be very valuable. However, a question we are not always explicit about answering follows: Why do we have laboratory work in the curriculum? What is distinctive about laboratory work that cannot be met elsewhere in the curriculum?

■ REPORTED AIMS OF LABORATORY WORK

The literature is replete with proposed goals for inclusion of laboratory work, and as well as being extensive, these are often contradictory. Reflecting this, surveys of faculty teaching introductory courses,[9] organic courses,[10] and physical courses[11] indicate a broad variety of goals for laboratory work, and with such scope, individual faculty can decide in the laboratories that they run what the goals of their laboratories are.[12] This leads to confusion and misalignment of student expectations and faculty goals.[13,14] Therefore, a core problem with having a lot of proposed goals and touted benefits for laboratory work is that the purpose of this laboratory work in the curriculum will be different for different faculty.[9] A similar conclusion was found in a review of high school chemistry education, reported in *America's Lab Report*, which stated the following:[15]

> *Researchers and educators do not agree on how to define high school science laboratories or on their purposes, hampering the accumulation of evidence that might guide improvements in laboratory education. Gaps in the research and in capturing the knowledge of expert science teachers make it difficult to reach precise conclusions on the best approaches to laboratory teaching and learning [p 2].*

There are several compilations of goals for laboratory work in the literature, describing the advantages that will be obtained from inclusion of laboratory work in curricula.[16−20] Reid summarizes the variety of goals of laboratory work succinctly, describing them under four headings: (i) skills related to learning chemistry, (ii) practical skills, (iii) scientific skills, and

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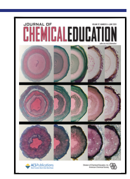

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(iv) general (or transferable) skills.[19,20] These appear sensible, and anyone involved in laboratory work could align aspects of their laboratory curriculum to these headings. However, from the perspective of seeking pedagogic goals for *laboratory* work (that is, considering the unique role of the laboratory), challenges to these goals emerge, and they are considered in turn below.

The first goal relates to learning chemistry theory in the laboratory. The intention of making chemistry real by illustrating ideas and concepts from theory has little evidential basis, as noted in the Hofstein and Lunetta reviews,[21,22] and indeed, this led to the editorial cited at the head of this commentary. Even in cases where evidence emerges, is this a suitable rationale? The laboratory is an expensive environment to teach theory, and even if that was not a consideration, which theory would be selected? Why would we choose a kinetics experiment but not a thermodynamics one? Woolnough and Allsop dismiss this rationale more strenuously in their book,[23] arguing for the cutting of 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 continual linking of practical work to the content syllabus of science [p. 39].*

The second goal of teaching practical skills is clearly grounded in the sense of a chemist's identity, as alluded to above.[6] However, we have a confusing arrangement in most undergraduate laboratories, in that while we aim to use them as a place to teach chemical technique, we tend to assess them by a laboratory report. Some notable exceptions to this have been summarized elsewhere,[24] but it is known that the assessment protocol reduces the value of laboratory time in the minds of students at junior[13] and senior[25] levels. The latter study reported that senior students put equal weight on the categories "use instruments and techniques" and "minimize time spent in the lab". DeMeo has written a survey of teaching of chemical technique,[26] but much of this focuses on preparation in advance of the laboratory, as well as the role of mental preparation, influenced by Beasley's work in the late 1970s. This also preempts a question for modern times with the emergence of virtual reality as an alternative to laboratory work.[27] Are we ready as chemists to justify the physical experience?

The third goal is scientific skills, and Reid summarizes these as the opportunity to learn skills of deduction and interpretation, to appreciate the empirical as a source of evidence, and to learn how to devise experiments. As with practical skills, these appear inarguable, but a question hangs over much of the quality of laboratory teaching, and whether typical approaches fulfill this goal. While there is much recent literature on the limitations of current laboratory approaches, Ausubel's scathing lines written in the 1960s were prescient:[28]

> *...students were coerced into mimicking externally conspicuous but inherently trivial aspects of scientific method. They wasted many valuable hours collecting empirical data which, at the very worst, belabored the obvious, and at the very best, helped them rediscover or exemplify principles which the teacher could have presented verbally and demonstrated visually in a matter of minutes. Actually, they learned precious little subject matter and even less scientific method from this procedure.*

The final goal is the development of transferable skills, and the laboratory is obviously a place where transferable skills such as team-work, time-management, and problem-solving can be developed. However, these are not unique to the laboratory, and there is a danger that the laboratory will become home to activities that develop transferable skills, not because of the laboratory environment but because it is a place which facilitates a better staff/student ratio necessary for assessment and management of activities which can develop these skills. It is the role of all aspects of the curriculum to develop transferable skills, and the laboratory should not be uniquely isolated as the place where this important aim is developed because of convenience.

■ ESTABLISHING A PEDAGOGIC BASIS FOR PRACTICAL WORK

The preceding discussion has aimed to offer a critique of the generally reported goals of laboratory work either in querying their inclusion as goals or querying how effectively those goals are met in reality. The purpose of this commentary is to set out what is distinctive about laboratory work that cannot be met elsewhere in the curriculum, and rather than a catch-all space where lots of goals could be achieved (but are not), I consider that we would be better placed by situating the laboratory as a place where a very specific goal unique to that environment is achieved.

Reid's summaries of laboratory goals, described above, included "scientific skills". In his book, Anderson distinguishes between "science" and "sciencing", with the latter being the processes a scientist engages in while doing science.[29] This involves drawing on science knowledge and making use of it to conduct and plan experiments, interpret data, make conclusions, *etc.* Kirschner picked up on this argument, distinguishing between the "substantive" structure of science (the information that makes up the body of scientific knowledge) and "syntactical" structure of science (the way that scientists draw together this knowledge in the doing of science).[30] Both authors argue that the different environments of lecture hall and laboratory align well to these different aspects of science, and that the laboratory is best suited to teaching students how the process of "doing science" works. This reduces the pedagogical goal of chemistry laboratory work to a single statement, "*the place where students learn how to do chemistry*", noting especially that *learning how to do* chemistry is different from *doing* chemistry.[28] This concept of "doing" necessitates incorporating literature on the nature of science,[31] a topic that aims to describe "what science is, how science is done, and who does it".[32] Russell and Weaver's work is an important contribution to the chemistry education literature describing how different teaching approaches lead to differing student conceptions of what doing science means, within the context of chemistry as a science.[32] Noting Chang's work on the unique identity of chemistry[6] means we must explicitly describe what doing science means in the context of doing chemistry, and the consequent role of the teaching laboratory in developing that capacity, especially relating to the teaching of laboratory techniques.

In an effort to frame the learning environment and how to support learning within chemistry contexts, we have recently elaborated on considering laboratory learning as a "complex learning environment", whereby students need to draw together constituent skills, including learning the requisite practical skills, and knowledge, and applying them to a scientific task.[33−35] This framework leads to a single-minded approach whereby the

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purposes of all activities within the laboratory are focused on achieving the goal of learning how to do chemistry. The components of this can be made more tangible by drawing on, for example, the scientific practices identified as part of the Next Generation Science Standards at the high school level, which echo Anderson's concepts of "sciencing"[29] and include asking questions and defining problems, developing and using models, planning and carrying out investigations, and constructing explanations,[36] and there are examples of such approaches in the chemistry education literature.[37,38] This facilitates a much easier consideration of how laboratory curriculum progression can be designed through a chemistry degree program, as the sole focus becomes that of how students' ability to do chemistry progresses through the years of their undergraduate degree.[34]

■ CONCLUSION

The laboratory is part of a chemist's identity, but as educators we need to be much clearer on its pedagogic basis and the advantages that laboratory work add to our curricula. This commentary seeks to dispense with some ancillary goals of laboratory work and focus on the role of the laboratory as one where students learn how to do chemistry.

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Notes

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