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A CHEMICAL LABORATORY IN A DIGITAL WORLD

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ABSTRACT

The chemistry laboratory as a teaching device has been perceived as important by teaching chemists from the time of Liebig. However, the current views of the usefulness of laboratory experiences in helping students learn chemistry are not necessarily unified on this point. In spite of this ambiguity, teaching chemists continue to support the use of laboratory instruction as a major tool in the educational process in undergraduate courses, even if considerable uncertainty exists concerning the nature of the contribution that this element of instruction makes to student learning. From a pragmatic point of view, digital technology has intruded on the continued development of the laboratory instructional process. Presented here is a discussion of the ways that digital technology can (has) enhance(d) the *current* laboratory-oriented instructional process. In addition, digital technology allows us to accomplish laboratory-oriented tasks that normally cannot be attained in the usual undergraduate environment, which is also discussed.

INTRODUCTION

This paper addresses the role of the laboratory in helping students learn chemistry, the current status of laboratory instruction, and the uses of digital technology to assist in the learning process. It is important to recognize that the educational process involves two intertwined components—learning and teaching. Of the two, learning, a student-centered process, is the more important. Teaching, a teacher-centered process, involves the teacher arranging an environment that encourages students to learn.

What is it about chemistry that historically seems to demand a laboratory component in the instructional process? One reasonable answer to this question can be found in the writings of Ira Remsen, an important figure in the evolution of American chemistry in the time period defined by the late years of the 19th century and the early years of the 20th century. Remsen described his initial encounter with chemistry, which, ultimately, led to a lifetime's worth of professional engagement in the subject. The following excerpt from Remsen's biography [1] provides insightful information.

> *"While reading a textbook of chemistry," said he, "I came upon the statement, 'nitric acid acts upon copper.' I was getting tired of reading such absurd stuff and I determined to see what this meant. Copper was more or less familiar to me, for copper cents were then in use. I had seen a bottle marked 'nitric acid' on a table in the doctor's office*

> *where I was then 'doing time!' I did not know its peculiarities, but I was getting on and likely to learn. The spirit of adventure was upon me. Having nitric acid and copper, I had only to learn what the words 'act upon' meant. Then the statement, 'nitric acid acts upon copper,' would be something more than mere words. All was still. In the interest of knowledge I was even willing to sacrifice one of the few copper cents then in my possession. I put one of them on the table; opened the bottle marked 'nitric acid;' poured some of the liquid on the copper; and prepared to make an observation. But what was this wonderful thing which I beheld? The cent was already changed, and it was no small change either. A greenish blue liquid foamed and fumed over the cent and over the table. The air in the neighborhood of the performance became colored dark red. A great colored cloud arose. This was disagreeable and suffocating—how should I stop this? I tried to get rid of the objectionable mess by picking it up and throwing it out of the window, which I had meanwhile opened. I learned another fact—nitric acid not only acts upon copper but it acts upon fingers. The pain led to another unpremeditated experiment. I drew my fingers across my trousers and another fact was discovered. Nitric acid acts upon trousers. Taking everything into consideration, that was the most impressive experiment, and, relatively, probably the most costly experiment I have ever performed. I tell of it even now with interest. It was a revelation to me. It resulted in a desire on my part to learn more about that remarkable kind of action. Plainly the only way to learn about it was to see its results, to experiment, to work in a laboratory."*

A number of useful conclusions can be drawn from Remsen's remembrances.

- Curiosity is an important factor when "doing" chemistry is at issue.
- The process of experimentation involves a cycle of observation followed by conclusion followed by action—often repeated and sometimes the cycle occurs quite rapidly.
- Remsen was originally interested in the "action of nitric acid on a penny." He learned the operational definition of the word "action," and other concepts, too.
- Remsen concluded that "personal knowing" was important and that it could only be obtained by experimentation.
- The factors involved in understanding Remsen's observations are *qualitative* by nature, for the most part.

Chemists are not very good at manipulating qualitative factors to understand a phenomenon. We prefer quantitative data. However, if we are to make sense of Remsen's experience, we have to be able to understand these initial qualitative ideas about the role of the laboratory and manipulate them to our own use; for example, to help students learn chemistry more effectively, we must bend our backs to the task of understanding such qualitative information

HISTORICAL ANTECEDENTS OF LABORATORY INSTRUCTION

The first formal laboratory-oriented instruction appeared in the early years of the 19th century at German universities.

1806	F. Stromeyer at Göttingen
1807	N. Fuchs at Landschut
1811	J. Fischer at Jena
1824	J. von Liebig at Giessen

The best known of these is Liebig whose chemical interest was analysis, although he is mostly remembered as an organic chemist who was involved in the early days of unraveling the nature of organic compounds in terms of radicals and functional groups. The data from combustion analysis of organic compounds led to empirical formulas, which were important in evolving the concept of functional groups. From the point of view of Liebig's interest in organic chemistry, he needed trained analysts, so he focused his teaching on the intellectual needs of his discipline. He trained chemistry students to become proficient analysts who could then become involved in the analysis of the substance that formed the basis of his interest in organic chemistry. Liebig's model for using teaching laboratories as precursors for conducting research has persisted for a very long time. Indeed, some teaching chemists today maintain that exposing students to research at a very early stage of their development is the best way to help students learn chemistry. [2]

THE CURRENT VIEWS OF LABORATORY INSTRUCTION

An inspection of the literature shows two dramatically opposed camps on the question of the usefulness of laboratory instruction in the educational process. One group considers laboratory instruction a worthless process; they do not see the pedagogical usefulness of such activities, probably because the Remsen-like experience is difficult to describe; it seems almost magical. On the other hand, there are many who will view laboratory instruction as a necessity and are willing to defend this point of view.

Several commentators have attempted to define the nature of laboratory instruction [3]. The laboratory should be a puzzle, not a land of the already known. It should not address issues that the student already knows to be true; that is, the laboratory should not be a place where the laws and concepts of chemistry are verified. In Pickering's words, "If laboratory is to illustrate something, let it be the scientific method. Let it be the place where experimental data drives conclusions." The laboratory experience, in Pickering's view, involves logical thinking and the willingness to be bound by data, which is the hallmark of science.

Another champion of the "necessary" point of view is H. I. Schlesinger, the great experimental boron chemist. Schlesinger [4] enumerated explicit goals for the laboratory. A laboratory experience should be designed to:

- Illustrate and clarify principles discussed in the classroom by actual contact with materials.
- Give the student a feeling of the reality of science by an encounter with phenomena, which, otherwise, might be no more than words. [Note the similarity of this idea to that of Remsen.]

- Make the facts of science easy enough to learn and impressive enough to remember.
- Give the student some insight into basic scientific laboratory methods and to train him/her in their use. [Note the relationship of this point to Liebig's general outlook in teaching students to do analysis.]

Using other words, we can summarize that the proponents of the importance of laboratory teaching generally agree that the process has several goals.

- Teach manipulative skills.
- "Understand" apparatus.
- Foster understanding of scientific inquiry.
  - Designing experiments.
  - Executing experiments.
  - Generating data.
  - Data analysis.
  - Interpreting data.
- Developing:
  - Attitudes toward science
  - Motivation
  - A control of science
  - A sense of success
- Concrete introduction to abstract concepts

THE CURRENT ENVIRONMENT OF TEACHING LABORATORIES

Domin (5) has created a taxonomy of laboratory instructional styles (Figure 1).

Figure 1. Descriptors of the laboratory instruction styles. [5]

	Descriptor		
Style	**Outcome**	**Approach**	**Procedure**
Expository	Predetermined	Deductive	Given
Inquiry	Undetermined	Inductive	Student generated
Discovery	Predetermined	Inductive	Given
Problem-based	Predetermined	Deductive	Student generated

The Domin scheme describes a laboratory instructional "style" in terms of three (3) descriptors—*outcome*, *approach*, and *procedure.* An analysis by Domin of a number of published laboratory manuals indicates that expository laboratories are the most commonly employed (as implied from the use of the lab manual analyzed) in teaching first year—introductory—laboratory courses. In other words, most laboratory experiments in which the beginning student engages are designed to prove something that the student already knows, a consideration that is contrary to Pickering's point of view. Domin observed that most experiments in most laboratory manuals engage only the lower order intellectual skills in Bloom's taxonomy [6], namely, knowledge, comprehension, application. Seldom are the higher order skills of analysis, synthesis, and analysis engaged.

RESEARCH-ORIENTED LABORATORY EXPERIENCES

A number of commentators [2] have suggested that Liebig's original concept, that laboratory should teach about research-oriented ideas, is a more effective approach to laboratory instruction. Research teaches the value of independent investigation and original thought. Original thought about chemical concepts is, perhaps, what beginning students of chemistry lack. A research experience stresses *how* and *why* rather than *what*. In addition, research is the medium by which chemistry changes and students should begin to understand early in their careers that chemistry is a viable and changing discipline—it is a work in progress; they should know the intellectual and physical methods by which the discipline changes. Recall Pickering's observation that "the hallmark of science is logical thinking and the willingness to be bound by data." Data, in the general sense, is observations that could be qualitative in nature (recall Remsen) as well as quantitative.

ESTABLISHING A LABORATORY-ORIENTED RESEARCH ENVIRONMENT

Most teaching chemists are familiar with laboratory-oriented research experiences at the graduate level. But to create this kind of experience at the undergraduate level requires a dependable model. The Cognitive Apprenticeship Theory (CAT) [7] has been shown [8] to model the environment that exists in laboratories engaged in chemical research. CAT described the craft of research and, accordingly, should form the basis for a description of an undergraduate laboratory experience that should begin to help students learn chemistry more effectively. Traditional apprenticeships are the most common form of learning outside of the formal education system. Apprenticeship is not didactic teaching, but it is teaching by observation, coaching, and successive approximations. The CAT has been shown [8] to fit exactly the research laboratory environment found in most universities. CAT describes the human factors and the important content-oriented factors and their interactions that can be used to create a research environment in, for example, the first or second courses taken in the usual chemistry curriculum, e.g., general chemistry and organic chemistry laboratory.

We have used the CAT model to create a formal undergraduate laboratory course that incorporates many of the elements of research from the students' standpoint.

DIGITAL TECHNOLOGY IN THE TEACHING LABORATORY.

Chemistry has become increasingly useful to an increasing number of students with a widening spectrum of professional interests that are not centered on chemistry, but include a large component of chemical thought. These students are not chemistry majors; rather they are studying disciplines, e.g., molecular biology and material sciences, that require a depth of understanding of core concepts equivalent to that of chemistry majors. If we are to continue to service this increasing number of students in general chemistry and organic chemistry, we need the assistance of teaching-learning techniques involving digital technology. The basic core problem in such environments, e.g., multiple—perhaps 60—small laboratory sections (~20 students) is the administration and logistics that involve the "busy work" of teaching and learning; for example, the creation, distribution, collection, grading, and record keeping of the classical elements of instruction such as homework, quizzes, and examinations. Classical laboratory instruction involves not only these elements of instruction, but, additionally, pre- and post-laboratory activities that must also involve the same kind of logistics of creation, distribution, collection, grading, and record keeping. Appropriate pre-laboratory activities are designed to prepare the student for his/her laboratory experience, while post-laboratory activities help the students integrate their laboratory experiences into their current personal knowledge, as described by the constructivist theory [9]. Digital technology can be used to intervene in the students' ability to collect high quality data and assist in the analysis of that data. In our course designed for biology students using the CAT model, key experimental techniques involve spectroscopy and titrations. By using computer controlled diode array spectrometers, students are enabled to collect vast quantities of reliable data in the UV-visible region of the spectrum. Thus, experiments involving these instruments can be repeated at will—a full spectrum requires ~ 10 seconds to capture in digital form—which also permits a student to perform reasonably sophisticated data analysis repeatedly and rapidly. We have adapted the principle of the Mariotte bottle [10] to create a fast titration process; a full titration curve can be obtained in digital form in ~ 15 seconds. Clearly, the advantages that accrue to the ability to obtain fast and reproducible spectroscopic data also apply to the titration data.

The point to this brief description of our instrumental approach in the general chemistry laboratory is that students are empowered with research-level tools to obtain quality and demonstrably repeatable data on fairly sophisticated chemical systems, e.g., unknown matrices that authentically reflect real world systems, e.g., soft drinks and other "supermarket-oriented" products.

The simulation of experiments is another use of digital technology in the beginning laboratory. In our view, simulations should *augment*, not replace, experiments. For example, appropriate simulations can be used to good effect to anticipate a wet laboratory experiment as a pre-laboratory experience [11]. Simulations also can be useful to extend wet laboratory experiments to produce an overall experience that is richer than the wet-laboratory experience alone. For example, a simple kinetic experiment (e.g., a clock reaction) can be performed by the student at room temperature on a desktop using simple equipment. But that experiment can be enriched by providing a simulation mode that requires the student to choose the usual experimental parameters, e.g., concentrations, as well as a temperature other than room temperature. By this approach, students can begin to collect data from which activation parameters for chemical processes can be extracted. Numerous examples of useful simulations can be found in the *Journal of Chemical Education*.

In summary, if we are to fulfill our laboratory-oriented teaching obligation to an increasing number of students based on a research model, we must involve the use of digital technology in:

- The administration and logistics of large multiple section courses.
- The intervention in experiments that students perform to produce greater amounts of quality data that allow them to make decisions and judgments about their experiments.
- Simulations which allow students to have a richer laboratory experience.

CONCLUSION

I have attempted to develop the essence of the importance of a laboratory experience in the effective learning of chemistry.

- It's a constructivist theory of learning, often driven by curiosity.
- Currently, the factors involved in this kind of teaching can only be described qualitatively.
  - Respond to curiosity.
  - Create motivation.
  - Engage in research.
- The factors that define a research environment are found in the cognitive apprenticeship theory.

These are the factors we must address if chemistry students are going to enjoy the educational benefit of a research experience starting at the entry-level chemistry courses.

Finally, undergraduate chemistry students must experience a research environment because it helps them learn chemistry and it represents the way that chemistry changes. It shows that chemistry is a dynamic discipline subject to change as new facts are revealed and our understanding of the extant facts change.

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