

THE ROLE OF THE LABORATORY IN CHEMICAL EDUCATION

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INTRODUCTION

The laboratory has been given a central and distinctive role in science education. The identity of the best kinds of experiences and how these may be blended with more conventional learning experiences has not yet been objectively evaluated. A clear direction for laboratory instruction based on research is not yet available to teaching chemists.

If we could decide what is accomplished in the laboratory, we could decide whether it can be accomplished in other, perhaps less complex, ways.

Before discussion the role of laboratory instruction in chemical education, it would be useful to consider the nature of the students who we teach in entry-level courses. Since chemistry has become the central science (Figure 1) because it deals with the molecularity of the

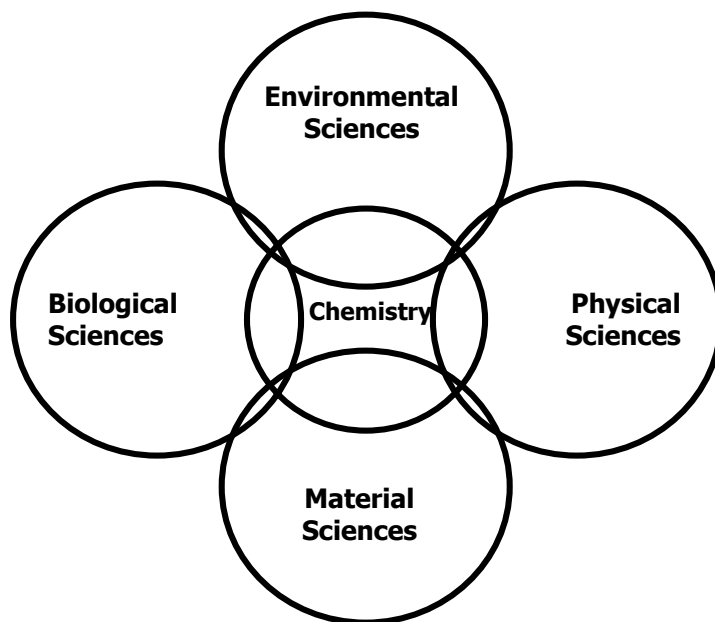


Figure 1. A Venn diagram illustrating the relationships of some ancillary disciplines to chemistry.

world and, hence, has important consequences with respect to many associated disciplines, it is reasonable to suggest that all educated people in our society should have a familiarity with some of the important aspects of our discipline. Thus, from one point of view, we are teaching a

cohort of young people who will become leaders in their chosen fields, namely, in commerce, government, the arts, and, of course, the sciences. I choose The University of Texas as an *example* of the diversity of students who a department of chemistry is expected to service. Of the ~ 6,000 entry-level students we serve each semester at The University of Texas, the non-science students—the commerce and the arts students—constitute about 35% of the total; the science students—those in the biological, physical, and engineering sciences—constitute approximately 62% of the class; and the chemistry majors are only about 3% of the students. Thus, most of the students we teach will not be professional chemists—a condition that is probably very common in many large institutions in the United States.

An understanding of chemical principles is important in the solution of many problems in the associated disciplines, those that rely on the core ideas of chemistry for their success (Figure 1). In addition, the subject of chemistry is a good model discipline with which to help non-science students appreciate the benefits of science to modern society. Chemistry is an excellent vehicle to help non-science students understand the process of scientific thought and the relationship of science to technology. Science is not technology, however, progress in technology rests on a firm foundation of science. Moreover, non-science students should learn the limitations of science as well as its potential. Well-educated students have always been expected to be well-versed in language and literature; in this era, the modern student should also be conversant with science, which has become a part of modern culture.

THE ANTECEDENTS OF CURRENT TEACHING METHODS

Most teaching scientists automatically, perhaps instinctively, assume that laboratory instruction will be a part of any science-oriented course to be taught. It is difficult to decide whether this point of view is an assumption based on historical precedent or whether it arises intuitively. An argument can be made that our current use of a laboratory component can be traced back to Liebig at Giessen, Germany in 1824, who said¹

At that time, chemical laboratories in which instruction was given in analysis did not exist anywhere; what people called such, were rather kitchens, filled with all sorts of furnaces and utensils for carrying out metallurgical or pharmaceutical processes.

Nobody understood how to teach analysis.

However, some would argue that the earliest source of the idea of a teaching laboratory was Friedrich Stromeyer who had one established in Göttingen, Germany in 1806.² Whatever the source of the idea, it is interesting that Liebig, who was instrumental in the beginnings of what we now call “organic chemistry,” exhibited such a great interest in analysis. One interpretation of this rather unusual interest is that Liebig needed well-trained analysts to support his work in organic chemistry. From analysis, one could establish empirical molecular formulas, which, of course, are the basis of recognizing the existence of organic radicals like $-C_2H_5$, $-CO_2H$, $-COH$, etc. From this point of view, Liebig was also laying the groundwork for the relationship of students and their supervising professors, which persists today. That is to say, Liebig was establishing the concept of the modern research group that still persists today—students’ work supports the professional interests of the faculty.

The current expression of laboratory instruction associated with entry-level chemistry courses gives rise to logistic problems concerning qualified persons to lead the laboratory sessions and be responsible for equipment and consumables (chemicals). Even if such administrative logistic problems can be solved for, e.g., a lecture class of 500 students, serious pedagogical problems invariably arise concerning the relationship of the laboratory experience to the lecture components of the course. Invariably, there is the question of an inductive connection or a deductive connection; will the laboratory experience be more effective if it is *preceded* by subject matter presented in lecture, or will the laboratory experience be more beneficial if presented *before* the appropriate subject(s) in the lecture component? In any event, there is no single simple answer to such strategic questions, which often means that there is little attempt to make the lecture and laboratory instruction correlate with each other in some pedagogically useful way.

CURRENT LABORATORY INSTRUCTIONAL STYLES

A taxonomy of laboratory instruction styles has been reported (Table 1).³ The four

Table 1. Descriptors of the Laboratory Instruction Styles

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

distinct styles of instruction—*expository, inquiry, discovery, and problem-based*—can be differentiated by three descriptors—*outcome, approach, and procedure*. Logically, the outcome can be predetermined or undetermined; the approach can be inductive (where the students observe particular instances to derive general principles, or deductive, where the students apply a general principle toward understanding a specific phenomenon. Finally, the procedure can be either given by the instructor or generated by the student. The descriptors for each of the laboratory instruction styles appear in Table 1.

The expository style (sometimes called *verification*) of laboratory instruction is the most popular because it can be performed simultaneously by a large number of students with minimal involvement from the instructor, at low cost, and within a 2-3 hour period of time, all factors that represent serious logistic constraints when large numbers of students are involved. Montes and Rockly⁴ present the interesting results of a survey they made of science teachers' perceptions of expository or verification experiments; the results indicate that, even though teachers recognize that the primary advantage of expository (verification) experiments lies with the teachers and most of the disadvantages primarily affect the students, the teachers overwhelmingly continue to use expository (verification) experiments. Clearly the choice of experiments is based on expediency rather than pedagogy.⁴

Inquiry laboratories (Table 1) are inductive, have an undetermined outcome, and require that students generate their own procedures. Since the inquiry approach places more responsibility on the students, it's not surprising that student ownership over laboratory activities

increases, which results in students showing improved attitudes toward science instruction and to improve their ability to utilize formal operational thought.⁵ Properly executed,⁶ inquiry laboratories require students to devise plans that invite intellectual and pedagogic methods and they engage higher order thinking skills—hypothesizing, explaining, criticizing, and analyzing, judging evidence, inventing, and evaluating arguments.⁷

Discovery learning (Table 1) is meant to personalize the information students acquire, making it more meaningful and, thus, better retained. The discovery approach is inductive, which, some argue, brings the student closer to the frontiers of science.⁸ Discovery learning differs from inquiry learning with respect to the outcome of instruction of the procedures followed. In true inquiry instruction, the outcome is unknown to both the instructor and the student, the instructor *guides* the student toward discovering the desired outcome in a discovery learning environment, which is accomplished by giving the students directions for what they are expected to do. To emphasize this condition, discovery learning is often described as *guided* discovery.

A problem-based environment (Table 1) encourages students to apply their understanding of a concept to answer questions for which answers do not yet exist. The instructor adopts a more active role by posing questions or problems to the students, providing the necessary materials and moving the students toward a successful solution to the problem. The methods of solving the problem are secondary to the problem itself. As in the real world, the problem comes first and serves as a vehicle for investigating and learning.⁸ The problems are usually “open-entry,” that is, they possess a clear goal, but many viable paths exist toward a solution.⁹

The literature is silent on the relative effectiveness of any of the styles of laboratory instruction (Table 1). That is not to say that attempts have not been made to establish the effectiveness;¹⁰ rather, the available data are equivocal and the reader must judge the evidence. Controlled studies have not been reported and often the assessments provided are ambiguous. Where apparently well-described studies are available,¹¹ there was no statistical difference between instructional styles. Domin³ has concluded that “to better understand the effectiveness of each style, researchers must go beyond comparing the general learning outcome [of] student achievement. Research is needed that addresses which style of instruction best promotes the following specific learning outcomes: conceptual understanding, retention of content knowledge, scientific reasoning skills, higher order cognition, laboratory manipulated skills, better attitude toward science, a better understanding of the nature of science.”

Earlier research in the effectiveness of laboratory teaching was focused on the presumed uniqueness of the method. The results of research on the effectiveness of teaching methods also are equivocal. Thus, comparisons of laboratory instruction against a variety of other methods—lecture, demonstrations, programmed learning, audio visual, computer simulation, etc.—perhaps in the hope that less expensive methods of instruction other than laboratory methods produce the dreaded “no significant difference” conclusion.¹²⁻¹⁵ The persistence of such equivocal results for so long a period of time have been traced¹⁶ to a wide spectrum of possible explanations from improper theoretical approaches, poor research designs, inappropriate testing methods, and the difficulty of controlling variables. Two extreme views of laboratory instruction have arisen; laboratory teaching was essential to all sciences, or laboratory teaching was a meaningless ritual

and a waste of time and money. Clearly, the answer (if there is one) lies somewhere between these extreme points of view, suggesting that laboratory instruction is a complex process; perhaps, some aspects of laboratory instruction can be replaced by other techniques. However, there persists the suggestion that a core of important, perhaps necessary, characteristics that can only be attained through laboratory instruction.

The current view of laboratory instruction is that it has the potential for:

- Teaching manipulative skills
- Understanding the use of apparatus
- Fostering an understanding of scientific inquiry which includes:
 - Designing experiments
 - Executing experiments
 - Generating data
 - Data analysis
 - Interpreting data
- Developing:
 - Attitudes toward science
 - Motivation
 - Control of science
 - A sense of success
- Providing introductions of concrete examples to abstract concepts

COGNITIVE APPRENTICESHIP

If one accepts the idea that laboratory instruction does provide the basis for teaching important concepts in chemistry, then a model for effective laboratory instruction should be pursued. While students and their instructors might generally give undergraduate chemistry laboratories low ratings, those who toil in graduate research laboratories are typically enthusiastic, inspired, and excited about their activities. Chemists almost universally view as successful the processes involved in the education of chemistry graduate students. In fact, the role of the research experience is viewed so generally as positive, that in 1978, the Council on Undergraduate Research (CUR) was established to “support and promote high-quality undergraduate student-faculty collaborative research and scholarship”.¹⁸ Indeed, there is a modest, but regular stream of papers appearing in the literature that describe a variety of efforts at undergraduate research.¹⁹ A web site has been established to promote research opportunities for undergraduate institutions.²⁰ Thus, it would seem worthwhile to try to capture the positive attributes of graduate chemistry research laboratories as an effective model for the structure of undergraduate chemistry teaching laboratories.

Any successful theory of learning chemistry through laboratory instruction should match the attributes of the successful education of chemistry graduate students. However, while the intellectual skills and tasks being taught in chemistry graduate programs are quite complex, most of the traditional theories applicable to chemical education seem simplistic and naive when viewed in the context of graduate programs in chemistry. Our goal now is to articulate our reasons for suggesting that Cognitive Apprenticeship Theory²¹ is a good theoretical pedagogical construct for the laboratory education of chemistry graduate students. Accordingly, if it is a

useful theory describing the education of chemistry graduate students, it could also serve as the basis for structuring effective undergraduate laboratory programs.

Cognitive apprenticeship theory is a pedagogical model developed within the situated learning paradigm. The theory is inspired by the apprentice-master model of traditional crafts commonly found in non-formal instructional environments, but it has been adapted to "cognitive" or intellectual domains. The relationship of the classical apprenticeship theory to the formal education processes is well described by Collins, et al.²¹

The differences between formal schooling and apprenticeship methods are many, but for our purposes, one is most important. Perhaps as a by-product of the relegation of learning to schools, skills and knowledge have become abstracted from their uses in the world. In apprenticeship learning, on the other hand, target skills are not only continually in use by skilled practitioners, but are instrumental to the accomplishment of meaningful tasks.

Cognitive apprenticeship might be viewed as "learn by doing;" it is a sequentially guided learning process with expert models and expert feedback. Cognitive apprenticeship theory was originally used to describe several significantly different teaching processes; the teaching of reading comprehension,²² the teaching of creative writing,²³ and the teaching of the process of doing mathematics.²⁴ These involve very different intellectual processes and it is the great strength of the cognitive apprenticeship theory that it applies equally to the teaching of each of these intellectual skills. Since the paper by Collins, *et al.*,²¹ has appeared, a variety of different disciplines have successfully used cognitive apprenticeship theory for instruction in their respective disciplines. For example, the theory has been used in the teaching of physics,²⁵ the teaching of medicine,²⁶ and the teaching of pre-service teachers using hypermedia computer aided instruction.²⁷ A search on the internet usually reveals a variety of discussions involving the application of cognitive apprenticeship theory especially in the area of computer aided learning. In the teaching of chemistry cognitive apprenticeship theory has been used in the computerized instruction in the use of NMR²⁸ and is described in a number of tentative research proposals on teaching chemistry.

According to Collins, *et al.*,²¹ the characteristics of a good learning environment incorporates four dimensions: 1. Content, 2. Methods, 3. Sequence, and 4. Sociology. Each of these dimensions exhibits a number of components as shown in Table 2. In the discussion that

Table 2. Dimensions of Ideal Learning Environments.

Dimension	Components of the Dimension
Content	Domain Knowledge
	Heuristic Strategies
	Control Strategies
	Learning Strategies
Methods	Modeling
	Coaching
	Scaffolding and fading
	Articulation
	Reflection
	Exploration
Sequence	Global skills before local skills
	Increasing Complexity
	Increasing Diversity
Sociology	Situated Learning
	Culture of Expert Practice
	Intrinsic Motivation
	Exploiting Cooperation
	Exploiting Competition

follows, we further define and elaborate on each of these dimensions and note how their components apply to graduate chemistry laboratory education.

THE CONTENT DIMENSION

The content dimension of The Cognitive Apprenticeship Theory, according to Collins, *et al.*,²¹ incorporates four components: domain knowledge, heuristic strategies, control strategies, and learning strategies.

Domain Knowledge. Domain knowledge involves that collection of learned conceptual and factual knowledge and procedures that are readily identified with a given subject matter (in our case, chemistry). A brief reflection on this concept suggests that not just one set of domain knowledge exists for science or even for chemistry. Rather, there are many sets of domain knowledge, each particular to a specified subject matter; the knowledge needed to become proficient within a given subject matter area will differ with the subject matter area. Thus, those who teach graduate students in chemistry know that, while there may be some areas of overlap, the domain knowledge required for different specialties is different, e.g., research organic chemists differs from that required for research physical chemists. Even within a single area like organic chemistry, each subdivision of organic chemistry will have unique components in its domain knowledge. Graduate students doing laboratory work in different sub-disciplines of chemistry almost always acquire different sets of domain knowledge.

Heuristic Strategies. Heuristic strategies are defined by Collins, *et al.*,²¹ as the “tricks of the trade” within an intellectual specialty. These are the strategies used by experts to perform the activities required by those in the discipline. Many such strategies are acquired over a lifetime of work and are often not obvious to the beginner in a field. Expert strategies often differ dramatically from the strategies used by novices in the field. The use of good heuristic strategies frequently distinguishes an expert from a non-expert in a field. In chemistry, heuristic strategies may deal with the physical manipulations required to perform a specified task or they may deal with the intellectual short cuts used to solve a synthesis problem or the development of the appropriate controls for a complex experiment. Many chemical fields have unique subsets of heuristic strategies. In many cases, the heuristic strategies used in research chemical laboratories have never been codified nor have they been written down. Often chemical heuristic strategies are passed from chemist to chemist by a novice’s observation of an expert performing a specified chemical task. Written instructions are often inadequate for the acquisition of the proper technique to carry out a given procedure in a chemistry laboratory. Thus, it is not uncommon for a chemist to go to another chemist’s laboratory to learn how to perform a given technique, *i.e.*, to acquire a new heuristic strategy.

Control Strategies. Control strategies are defined by Collins, *et al.*,²¹ as the collection of the techniques for the control of processes of carrying out the tasks at hand. They are the schemes used to select the heuristic strategies to be used for any given problem and when these are to be used. The components of control strategies are monitoring strategies, diagnostic strategies, and remedial strategies. Monitoring strategies are those strategies which help the student monitor his or her progress. For example, in the graduate research laboratory it is common that the students meet weekly with their advisor (mentor) to discuss the progress of their work and/or to provide written interim reports on the progress of their work. Many research groups require that all students give periodic oral presentations to the group. In such cases, the entire research group monitors the student progress. The diagnostic strategies are those strategies that are used to understand the source(s) of student difficulties and the remedial strategies are those strategies used to reduce or eliminate student difficulties. Actually, in modern graduate chemistry research laboratories sets of control strategies are implemented from the top down at many levels such as professor to student, from post-doctoral student to student, and from senior student to new student. In many research laboratories the control strategies are also implemented across the same level and from bottom to top. In good graduate research chemistry laboratories the progress of the group is monitored as well as the progress of the individual.

Learning Strategies. Collins, *et al.*,²¹ note that different tasks may require different learning strategies. Different tricks of the trade are used for different tasks. Different problems require different approaches. Certainly a student in a graduate research chemistry laboratory uses many different learning strategies. For example, some chemical knowledge is best acquired by reading, some by listening to formal and informal lectures, some by attending formal courses, some by observation of the laboratory techniques of others, some by doing the experiment, some by trouble shooting a malfunctioning instrument, some by writing laboratory reports, some by preparing an oral presentation, etc.

THE METHOD DIMENSIONS

According to Collins, *et al.*,²¹ the method dimension exhibits four components; modeling, coaching, articulation, reflection and exploration.

Modeling. Modeling is the student's observation of an expert doing a task. Modeling is one of the essential components of graduate research chemistry education. Graduate students learn by watching the experts in the laboratory perform different tasks, be they physical manipulations, computations, report writing, or whatever task is at hand. This observation of experts takes place at all levels. The new student watches the second year student and they, in turn, observe others with more experience; the second year student watches the third year student, etc., the graduate students watch the post doctoral students and every body watches the professor. As Collins, *et al.*,²¹ noted, more than observation is needed; the student may also need to be provided with a narrative of why the expert is doing the task in a certain manner. Such narratives occur all the time in a research laboratory, most are informal, but some are quite formal.

Coaching. The activities of observation go both ways in a good research laboratory. Not only does the student watch some one with expert knowledge of the task, but also the teacher then watches the students perform the various tasks and then provides suggestions to the students for means for the students to improve their implementation of the task at hand. This activity is called *coaching*, which is the observation by an expert of student actions in carrying out a task coupled with feedback by the expert. Coaching focuses on the enactment and integration of skills towards the attainment of well understood goals through interactive immediate feedback and suggestions. Coaching has two levels of action. At first, the instructor provides a significant number of supports to the students, called *scaffolding*, as they learn how to perform a given task. Such supports can be intellectual, physical, or algorithmic. The second part of coaching is called *fading*, which consists of the gradual removal of the scaffolding supports from the students until they are performing their tasks without supervision or support. The activities of coaching and fading are key components of graduate chemical education. At the beginning of the students' graduate career they need to be provided with extensive support at all levels in their learning of the process of performing chemistry research. By the time the students have completed their graduate programs and are awarded the Ph. D., they are ready to train other students in the process of chemistry research.

Articulation. Collins, *et al.*,²¹ define articulation as the process of having the students express in clear and effective language their knowledge, reasoning, and problem solving strategies. The articulation process is deeply rooted in the laboratory education of a chemistry graduate student. Students prepare and deliver formal and informal talks and/or posters about their research and how it fits into the research goal of the group. These talks and/or posters are given at multiple levels; the presentation to the research advisor, presentation to the research group, presentation to the division within the chemistry department, to the department as a whole, and at regional and national meetings. Not only are students expected to prepare and give oral presentations, they are expected to prepare written reports for journal publication and grant preparation, etc.

Reflection. Collins, *et al.*,²¹ define reflection as the process of the students comparing their knowledge, reasoning, and problem solving strategies with those of an expert, another student, and ultimately an internal cognitive model of expertise. The reflection process is integral to graduate chemical education. Students are constantly comparing their strategies and knowledge with others in the research group, the department, and the profession.

Exploration. Collins, *et al.*,²¹ define exploration as the process of guiding students into modes of problem solving on their own. Such exploration is fundamental to graduate education. One of the key attributes that examiners look for as evidence that chemistry graduate students are ready to be awarded a Ph. D. is their ability to develop and implement research strategies for the solution of chemical problems. Indeed, it is the ability to do so that is the key attribute that separates those with a Ph.D. from others in the profession. The progress of a graduate student from a novice to a skilled professional can be measured by the increasing ability of the students to solve problems on their own.

SEQUENCE DIMENSIONS

The sequence dimensions incorporate global skills before local skills, increasing complexity and increasing diversity.

Global Skills Before Local Skills. The sequence dimension of global skills before local skills is the concept that students should first build a conceptual model of the target skill or process. It is only after they have built this conceptual model that they should start learning how to perform each of the detailed components of that target skill in an expert manner. In other words, the student should know what the goal of the research is before they start learning all the skills that will lead to the desired research end product. The development of global skills before local skills is inherent in the training and education of chemistry graduate students. Students are taught from the beginning that the research group's goal is, e.g., to synthesize a certain compound, design a specific process, or understand a certain phenomena. After a few months of training, almost every new graduate student in a research group will be able to describe the research goals of the research group to a visitor even if these same students have yet to learn how to perform most of the tasks needed to reach that goal.

Increasing Complexity. The sequence dimension of increasing complexity was defined by Collins, *et al.*,²¹ as the construction of a sequence of tasks where an increasing number of skills and concepts and their integration is required for expert actions. The intellectual growth of a graduate student can be measured by the skills and knowledge they have acquired. The new student has some knowledge of chemistry and a few laboratory skills learned as an undergraduate and/or on the job. Beginning students rarely have the ability to define an entire problem, devise a path to the solution of that problem, and then carry out the experiments to provide the information needed for the solution of the problem. However, the chemistry graduate students' educational progress can be measured by their increasing ability to perform various laboratory manipulations; to design experiments and to evaluate the results of those experiments; to evaluate the research results of others; to string together a series of experiments to solve the problem(s) at hand; to prepare and present the results of these experiments; and to place such results with a proper perspective within the known scientific knowledge. Such

abilities require a large number of different skills and are almost always built from the simple to the complex.

Increasing Diversity. According to Collins, *et al.*,²¹ the sequence dimension of increasing diversity is the construction of a sequence of tasks where a greater variety of skills and concepts are required for expert actions. As was noted in the discussion above on the sequence dimension of increasing complexity, not only do the tasks learned in the education of chemistry graduate students become more and more complex, they also become more diverse. A successful Ph. D. candidate is able to perform a wide variety of different tasks and has a professional knowledge of a wide variety of chemical ideas and facts.

SOCIOLOGY DIMENSIONS

According to Collins, *et al.*,²¹ the sociology dimensions have the following components: situated learning, culture of expert practice, intrinsic motivation, exploiting cooperation, and exploiting competition.

Situated Learning. Situated learning, according to Collins, *et al.*,²¹ is the provision of an environment that reflects the multiple uses to which the students' acquired knowledge will be used in the future; that students understand purposes and uses of their acquired knowledge; that students learn by actively using their new knowledge; and that students are made aware of the various situations where they may use their knowledge. Two of the primary functions of university chemistry research laboratories are: 1) to teach graduate students how to conduct research in chemistry and 2) to conduct research in chemistry. Graduate students learn how to do chemical research by doing chemical research and by observing others (students, postdoctoral fellows, and faculty) do chemical research. Chemistry graduate students acquire their knowledge in an environment in which they can see use of their acquired knowledge and thus can understand the purpose of the various forms of the instruction they receive. Given the extensive interaction of students within a university chemistry research laboratory and the extensive written and oral communication within the community of scientists, students are usually made aware of the various situations in which they may use the knowledge and skills that they acquire in their graduate education.

Culture of Expert Practice. The culture of expert practice is defined by Collins, *et al.*,²¹ as "providing an environment in which students actively communicate and engage in the skills of expertise; expertise is understood as the process of efficiently and accurately solving problems and performing specific tasks of the discipline." Simply put, the students learn to think like experts. This is one of the key components of chemical graduate education. The chemistry graduate student is immersed in the culture of expert practice in chemistry. The entire training of a chemistry graduate student is focused upon making them an expert in their particular field. They are constantly exposed to expertise in the laboratory, in the department's technical lectures, in the extensive chemical literature, and at the regional, national and international chemistry meetings. Expertise is expected; lack of expertise is noted and corrected and sometimes chastised.

Intrinsic Motivation. Intrinsic motivation is defined by Collins, *et al.*,²¹ as "students becoming involved in the learning process because their success will lead to the attainment of

interesting and coherent goals.” One of the key features of chemical graduate education is the inherent combination of goals in graduate education. First, students know that by completing their graduate education they have the opportunity to have a career in the excitement of advancing knowledge in chemistry. At the same time the students understand how their immediate successes in the acquisition of knowledge and skills will aid in the attainment of both the short term and long term of goals of the research group. We believe that this fairly unique combination of short- and long-term goals is one of the reasons that graduate chemistry education is so successful.

Exploiting Cooperation. Exploiting cooperation is defined by Collins, *et al.*,²¹ as “learning through cooperation.” They note that such cooperation is a powerful motivator and a powerful mechanism for the extension of teaching resources. The day of the independent chemist working by his or herself is all but gone. The components of modern chemical research are so complex and the skills needed are so diverse that most all of today’s chemical research is performed by teams of scientists, each with their own expertise. Teamwork is an essential component of modern chemistry graduate education. Graduate students join research groups; it is there that students learn their subject and where they acquire their training. Cooperation is a distinctive part of the chemistry graduate education experience.

Exploiting Competition. The last of the sociology dimensions as defined by Collins, *et al.*,²¹ is exploiting competition. They note that competition is an important factor, but one that has serious potential deleterious effects. Any one who has been involved in the excitement of original research knows that scientists are very competitive. The glory goes to those who publish first. Priority of discovery is a key to recognition and status in the field. In fact, those who are second in the presentation of discoveries, etc., are frequently denied publication at all. This competition for priority in publication is true for those who wish to patent discoveries, obtain grants, and is equally true for those who are rivals for prizes like the Nobel Prize. Graduate students in chemistry are constantly made aware of the importance of being first in discovery and publication. This awareness of priority of publication is a strong motivation for long hours of hard work and within a research group the understanding that such effort is needed from all members of the research team. Exploitation of competition is, indeed, a prominent feature of the social structure of chemical research and of the education of chemistry graduate students.

From a global perspective, the Cognitive Apprenticeship Theory incorporates many of the currently popular instructional strategies—collaborative learning, constructivist theory, Piagetian approaches, the meaningful learning ideas of Ausubel, etc.

Acceptance of the cognitive apprenticeship model for laboratory learning has a number of important implications for the design, development, and evaluation of laboratory courses; 1) laboratory courses should have the clear goal of providing the student with acquisition of expert practices; 2) the knowledge acquired by the student should have a clear value to the student and the student should be aware of that value while taking the course; 3) a good laboratory course will require feedback from the student to the instructor and feedback from the instructor to the student; 4) if chemistry laboratory courses are meant to reflect the use of chemistry in the real world, then the course program must be a coherent, in-depth sequence; 5) chemical thought changes in the real world, e.g., of the life sciences, and those changes should be reflected by

changes in the technologies taught in the laboratory courses; 6) any attempt to teach students the actual process of acquiring chemical knowledge in the laboratory must model actual chemistry laboratory experiments, not demonstrations. Other implications, which we choose not to delineate here, are certain to occur to the interested reader.

CONCLUSION

Although some may not agree with the details of this analysis, the general conclusion—that laboratory instruction does, indeed, have a role in students' understanding of chemistry—placed in context with the current (theoretical) trend that science education is critical in the education of all citizens leads to the observation that *every student* who takes a chemistry class should have an associated *laboratory* experience that is as close to that promised within the cognitive apprenticeship model as practical if he/she is to have a meaningful learning experience (in the chemical sense). This may be a very difficult condition to establish for *every student*. However, some of the techniques made possible by modern technology¹⁷ may be helpful in this respect.

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