

# Adapting the Undergraduate Chemistry Laboratory to Contemporary Learning Theory

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## **ABSTRACT**

The value of the laboratory to science learning has been under scrutiny. This thesis examines the undergraduate chemistry laboratory and seeks to show how improvements in student outcomes will result from reformulating the laboratory in accordance with contemporary learning theory. First, this thesis examines the traditional undergraduate chemistry laboratory from the perspective of cultural historical activity theory to determine what inconsistencies possibly exist. The thesis then considers factors influencing the structure of the traditional laboratory, the nature of learning assumed by the traditional lab and factors influencing students to show how these form barriers to learning in the laboratory. Third, the thesis explores contemporary theories of learning and how they accommodate individuals and how they promote deeper conceptual understanding. Subsequently, the thesis investigates research into laboratory learning, both laboratory variables and influences on students, to determine their effect on learning. This enables the thesis to reconceptualize the undergraduate chemistry laboratory and analyze whether the incompatibilities of the traditional lab with deep learning are alleviated or resolved.

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## CHAPTER 1: INTRODUCTION

What is proposed here is a greater recognition of the breadth of potential outcomes of laboratory work to ensure that laboratory experiences do not focus solely on conceptual learning and the acquisition of various laboratory techniques but also facilitate the development of investigative skills...laboratory experiences ... should also be considered to have a central role in the teaching and learning of investigation and problem solving skills (Garnett & Garnett, 1995, ¶ 23.)

Laboratory instruction is an integral part of undergraduate chemistry studies in university. However, practical work largely fails to achieve its potential as a rich learning experience. The underlying problem relates to antiquated theories of learning forming the basis of instruction. This thesis argues that by reformulating the laboratory in accordance with contemporary learning theory it is possible to change the chemistry laboratory curriculum to enhance learning and scholarship.

Over past decades, scientists and curriculum developers have been responsible for changing the school curriculum. While they commonly have great subject area expertise, the main contributors to university chemistry curricula have had little formal education as curriculum developers and are typically unfamiliar with theoretical perspectives on science learning (Duschl, 1985), emphasizing content instead. Even notable scientists like Carl Wieman, the physics Nobel laureate who is taking an active role in shaping university science education, has succeeded thus far in simply reproducing ideas that are already



familiar in the education literature (Wieman, 2008). In part this is due to the reluctance of scientists to accept the “soft” research of the humanities (Latour & Woolgar, 1986).

Scholarship in refereed publications has focused on the “teaching” rather than on the “learning” of science (Bodner & Weaver, 2008; Johnstone, 2000). A perusal of *University Chemistry Education* (U Chem Ed), *Chemistry Education: Research and Practice* (CERP), and the *Journal of Chemical Education* (J Chem Ed) confirms this concentration. Much of this focus is lecturing; there is a paucity of research on the undergraduate chemistry laboratory. Furthermore, the available research appears inconclusive (Nakhleh, Polles, & Malina, 2002). Recently, Avi Hofstein and Rachel Mamlok-Naaman (2007) pointed out the need to research the variables in the laboratory setting that affect student learning, factors such as learning objectives, students’ perceptions of the objectives, interactions in the lab, and the preparation, knowledge, attitudes, and behaviours of the instructor.

Laboratory practice does not appear to capitalize on its advantages of relatively small class sizes, longer instruction periods, and various types of interactions that can occur to make comprehension possible. The less formal atmosphere of the lab provides more opportunities for constructing knowledge, through collaboration, extended investigations, and discussion (Tsapalis & Gorzei, 2005). Yet the lab is an ineffective milieu for learning; Rosalind Humerick’s (2002) students all agreed that most lab learning occurred in the lecture hall. To reveal why this contradiction exists, I describe a typical undergraduate chemistry laboratory beginning with a vignette of students interacting in the

lab (based on over 14 years as an instructor) followed by a CHAT (cultural historical activity theory, clarified below) analysis in Chapter 2. To flesh out this analysis, I add details from course outlines, lab manuals, interviews, and personal recollections from notes. With this thick description in hand, I note disconnects and contradictions characteristic of the lab. This leads me to examine the history of lab instruction in Chapter 3 and explore the learning theory(ies) that underlies laboratory instruction as a way to identify the source of problems. What do these theories convey about the subject material and what do they convey about the learner? To gain a deeper sense of the limitations of the traditional teaching theories that have predominated in science education, I discuss more recent sociocultural theories of learning in Chapter 4. I explore how these recent theories perceive the learner and demonstrate how they can help overcome the problems inherent in the usual lab situation. With this theoretical underpinning, I reconceptualize the chemistry laboratory in Chapter 5 and portray it beginning with a new vignette, a revamped course outline and lab materials, and with reflections from practice. I assess the redescribed lab situation for resolution of the problems inherent in the traditional lab and look for potential problems. In Chapter 6, I summarize the implications for chemistry laboratory curricula and propose suggestions for further research.

First, however, I must define what constitutes effective laboratory learning. What skills and abilities are appropriate for obtaining an undergraduate degree with a chemistry major? I discuss these in the section below. Second, I outline the development and

principles of cultural historical activity theory, CHAT. In Methods, I justify selecting CHAT to analyze activity in the laboratory.

### **Benchmark for Effective Laboratory Learning**

Given that the laboratory fails to meet expectations for student learning, what attributes and knowledge do we expect of students who have pursued practical work as part of their studies? Hodson (1992, 2003) proposed four elements:

1. *Learning science*: conceptual and theoretical knowledge of science.
2. *Learning about science*: nature of science, methods, processes, history, interactions, implications.
3. *Doing science*: engaging in scientific inquiry and problem solving of real world tasks.
4. *Engaging in socio-political action*: critically thought-out action in social, political, economic, environmental and moral/ethical concerns.

We are aware of the emphasis on the first element, learning science, within the academy.

The prevalence of myths of science (Bauer, 1992; Shamos, 1995) indicates that the laboratory does not adequately deal with the nature of science, or with its processes and methods in spite of its purpose to that end. Although individual institutions have modified their courses towards inquiry labs (for example, Ditzler & Ricci, 1994), the questions studied are those of chemical relationships and laws rather than contemporary problems.

Thus, the third and fourth elements are not addressed, and the second only poorly.

Entirely absent is any reference to the dissemination of science through reading, writing, and speaking.

Hodson's elements offer a general guideline to aspects of science education but do not define particular characteristics. What students learn about science and learn to do in the laboratory often differ from what the professor or instructor assumes they know. The literature on scientific literacy and specifically the idea of levels of scientific literacy offer a more explicit benchmark.

Shamos (1995, pp. 87-90) introduces a hierarchy of scientific literacy to which I add a fourth level advocated by Hodson.

1. *Cultural Scientific Literacy*, the simplest form. This includes a grasp of certain background information in names, dates, discoveries, and some science jargon but an inability to converse on science topics. The individual at this level can answer trivial game questions.
2. *Functional Scientific Literacy*. This level includes being able to read, write, and converse logically in meaningful discourse on topics appearing in the popular press. More everyday science and vocabulary is familiar and used in context. However, the individual cannot consistently discern between pseudo-science and robust science.
3. *"True" Scientific Literacy*. Here individuals have an understanding of the processes of science and the role of theory in the practice of science. They are aware of the foundations of science, some major theories, analytical and

deductive reasoning, objective evidence, the central role of mathematics, etc., in short, the skills and knowledge of professional scientists and engineers.

4. *Critical Scientific Literacy* (Hodson, 1992, 1999). This level probably lies between levels 2 and 3 of Shamos although not all truly scientifically literate people are necessarily also critically scientifically literate. These individuals recognize the interrelations of science/technology with political and economic might, as well as the societal and environmental impacts of scientific and technological innovations. They have personally decided their stance on important local and global issues and are sufficiently familiar with government, industry, and commercial decision-making to have the ability to prepare for and take action on socio-political issues.

Hodson's level is important since scientists and medical researchers are funded by or work for industry and are pressured to get the results favourable to industry. Individuals require critical scientific literacy in order to determine for themselves the validity of expert knowledge that may be biased.

Given the above discussion, what skills and abilities are appropriate for obtaining an undergraduate degree with a science (chemistry) major? Students are pursuing content knowledge, knowledge about chemistry. They also learn about science and learn to do their particular branch of science, albeit with different outcomes at different institutions and different professors and instructors. What skills are emphasized depends on the

program, whether applied chemistry for industry or pure chemistry for a career in chemistry research or academia.

The industrial view looks for trained workers for production and profit. Scientifically literate employees possess subject knowledge, cognitive skills, and transferable personal skills (Duckett, Garratt & Lowe, 1999, Phillips, 2001). The latter includes skills in written and oral communication, time management, interpersonal relations, numeracy, and IT—information technology (Bailey, 2001). Cognitive abilities incorporate practical skills, problem-solving skills, and interpretive skills. Science literacy resides in the individual (Figure 1.1a). Chemical research falls under “true” scientific literacy but often neglects to cultivate adequate personal/transferable skills. However,

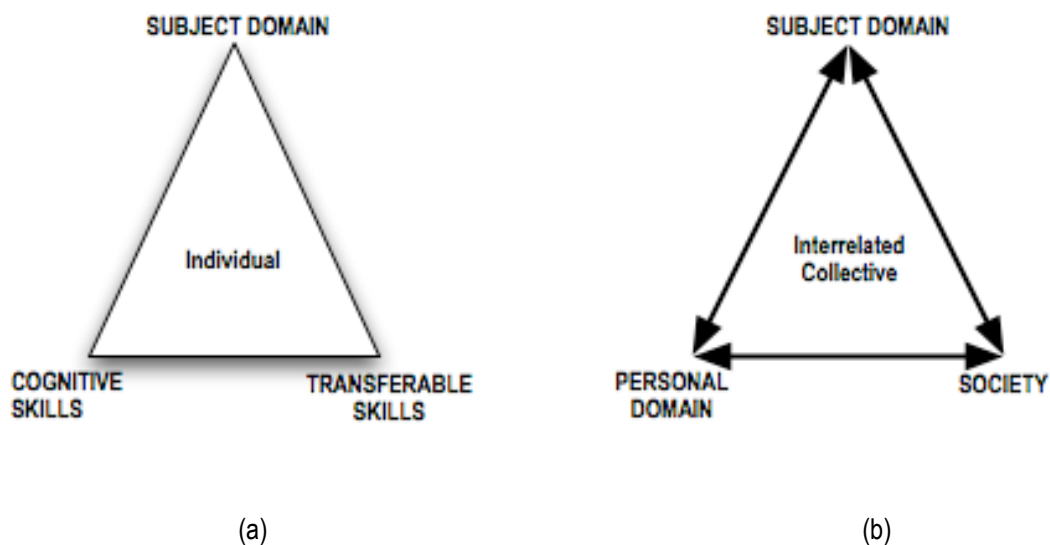


Figure 1.1. Interrelationships of scientific literacy for (a) industry and (b) responsible citizenship (de Zoete, 2008).

Hodson's vision of critical scientific literacy considers the interrelations among the domains of person, society, and subject (Figure 1.1b), providing space to develop these personal skills. The personal domain includes character, attitude, and intellectual and communication skills; the society domain includes co-operative learning, social values, and socio-scientific decision-making; and the subject or nature of science domain includes inquiry or investigatory skills (Holbrook & Rannikmae, 2007, p. 1352). Content is thus dependent on context, the issues that are relevant in the culture, and is regionally bound. Following Roth's proposal (Roth, 2007b; Roth & Lee, 2002; Roth & Barton, 2004), scientific literacy emerges from this collective practice in situ; scientific literacy is emergent in time and space.

There is support for this vision. In looking towards science education for the twenty-first century, Osborne considers four contexts for scientific literacy: conceptual, cognitive, ideas-about-science, and the social and affective (Osborne, 2007). With science knowledge ever-expanding, what conceptual knowledge is most important becomes problematic. Cognitive skills include argumentation (rational, evidence-based explanation to support a specified standpoint), scientific reasoning, laboratory skills, facility with computers, and thinking critically. Understanding the epistemic nature of science requires examining one's beliefs and myths about science and learning about the tentative nature of science, how science knowledge develops, and the risks of science. The social and affective domain encompasses the creative and intuitive nature of scientific work, collaboration and support among the scientific community, and science for citizenship.

The Canadian Society for Chemistry, under the umbrella of the Chemical Institute of Canada, oversees national accreditation for undergraduate chemistry programs and sets accreditation guidelines (CSC website); among these is a minimum of 400 hours of laboratory work. Chemistry graduates should have core skills in content (academic competence), laboratory methods, computer and information technologies, communication, problem-solving, numeracy, and literacy. The level of knowledge and problem-solving will vary, dependent on the program emphases. Generally, science education stops here. Maienschein (1998) labels this “science literacy”, a conceptually-based, short-term vision with science playing a dominant role. However, this science literacy can be limited, attaining only the functional scientific literacy of Shamos described above and neglecting an understanding of scientific processes and of the political and economic influences on science. This type of science education is suited to the industry view of science literacy albeit interpersonal skills may be weak. In contrast, “scientific literacy” takes a larger view and promotes the personal and social aspects of science within sound scientific knowledge. This second vision is evident in STSE (science, technology, society, environment) education in elementary and secondary schools. Socio-scientific questions arise, and the best alternative after collaboration and discussion is sought since there can be no “right” answer. There is a possibility of critical scientific literacy beginning to be fostered here. The question then becomes what is our goal for chemistry students—science literacy or scientific literacy? Scientific literacy, by virtue of its collaborative nature to address relevant issues, supports the development of interpersonal skills, solving open-ended problems, communication, interpretive and evaluation skills, and interdisciplinary



skills. The principle of academic freedom would agree with giving students as many skills as possible and thereby encourage true, critical scientific literacy for university graduates.

The trend towards scientific awareness in order to deal competently with socio-political issues is quite evident in the literature. Yet at the tertiary level, it would appear that science and therefore chemistry courses are arranged primarily to teach content from the perspective of an expert in the field. Public schooling at all levels has attempted to incorporate new learning theory into their praxis but without exposure to new teaching in university, teachers often reproduce the old science instruction in their classrooms (Spencer, 2006). To make sense of this conundrum, I describe a typical undergraduate chemistry laboratory class and appraise it through the lens of activity theory in Chapter 2. However, first I introduce activity theory and explain its choice for this thesis.

### **Cultural Historical Activity Theory**

The genesis of activity theory lies in the research of the Soviet psychologist Lev Vygotsky. I trace the evolution of cultural historical activity theory, CHAT, beginning with Vygotsky's proposal that humans use signs or tools to mediate their actions. Following this historical background, I outline the basic principles of CHAT and then offer a critique of CHAT as a framework for analysis. I conclude the chapter with a methods section, detailing the relevance of CHAT to the chemistry lab.

### *Brief Evolution of Cultural Historical Activity Theory*

Vygotsky (1896-1934) sought to bridge natural science with mental or cognitive science in order to explain higher psychological functions. Sign operations, he believed, were the product of social development, a sign being any artificial or self-generated stimulus (Vygotsky, 1978). The link, then, between stimulus, S, and response, R, is not direct, but is mediated by the sign operations. The individual must be actively engaged in establishing the link, but the link is also capable of reverse action—the stimulus can act on the individual. In this manner, behaviour can be controlled from the outside, from culture (Vygotsky, 1978, p. 39-40). Thus human activity is both internalized as rules and standards and externalized in creating new rules and standards (Lektorsky, 1999). This has been identified as the origin of activity theory, or as Engeström puts it, as first generation activity theory (Engeström, 2001). Human action is mediated by culturally meaningful tools and signs. Collaboration with other humans creates what Vygotsky calls ‘zones of proximal development’ (Vygotsky, 1978, p. 85) in which learning and development can leap forward. This differentiates humans from other life forms. Vygotsky’s idea of cultural mediation by signs or semiotics overcame the individual/societal divide. However, the focus of attention was still the individual.

Vygotsky’s colleagues, Alexei Leont’ev (or Leontiev) and Alexander Luria, furthered this new theory to extend to object mediation. Together they referred to this approach variably as “cultural”, “historical”, and “instrumental” psychology, all of which implied cultural mediation in psychological processes (Cole, n.d.). Leont’ev changed the

unit of analysis from the individual to the collective and distinguished between activity, action and operation. “The uppermost level of collective activity is driven by an object-related motive; the middle level of individual (or group) action is driven by a conscious goal; and the bottom level of automatic operations is driven by the conditions and tools of the action at hand” (CAT & DWR). Collective activity then is connected to object or motive. Individuals are often not conscious of collective motives but are aware of goals in individual actions. Automatic operations, the lowest level, are dependent on the conditions in which the action is performed (Figure 1.2). While this second-generation activity theory offers three dialectically related levels of analysis, it neglects the intersubjective side of activity.

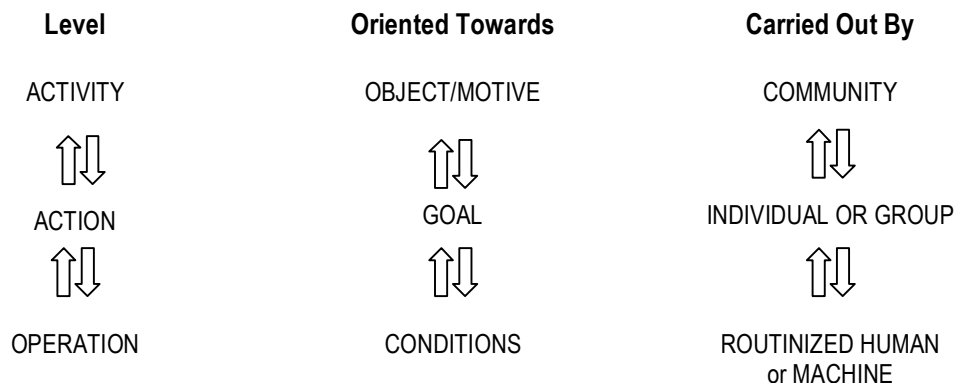


Figure 1.2: Leont’ev’s hierarchical structure of activity (University of Helsinki Center for Activity Theory and Developmental Work Research (CAT&DWR)).

Yuri Engeström incorporated these ideas in an expanded triangular form of Vygotsky’s model (Engeström, 1987). The top of the triangle is the instrument, or the tools and signs, which mediates the subject and the object (the latter located mid-way

along either side of the triangle). These three then form a smaller, upper triangle within the larger one to symbolize the production subsystem. Thus the production of an activity involves a subject and the tools or artifacts that are used in the activity to achieve the object through actions and operations. Rules and division of labour are the apexes at the bottom of the triangle, bisected by community. The community is integral in negotiating and mediating both the rules and division of labour. A smaller central triangle representing consumption is formed by the connections between the three midpoints of subject, object and community. “The subject must operate within a community that reciprocally supports the production activities of the subject but also consumes effort from the subject” (Jonassen, 2000, p. 101). Two more inner triangles complete the larger outer triangle: exchange on the left and distribution on the right. Distribution connects the object of activity to the community through a division of labour that is both horizontal and vertical. Finally, the exchange subsystem identifies the rules and customs, (both implicit and explicit), negotiated by the community in which the subject functions (Figure 1.3). While production is dominant and consumption has become subordinate to production, exchange and distribution, there is interaction between all of these modes. The bidirectional arrows signify reciprocal dynamic relations. The three tiers are representative of the three levels of Leont’ev. The concepts of production, consumption, exchange and distribution are reminiscent of Marx’s analysis of the capitalist socio-economic system, the contradiction lying between the exchange value and use value of a commodity. This contradiction is an integral part of all activity systems (Engeström, 2001).

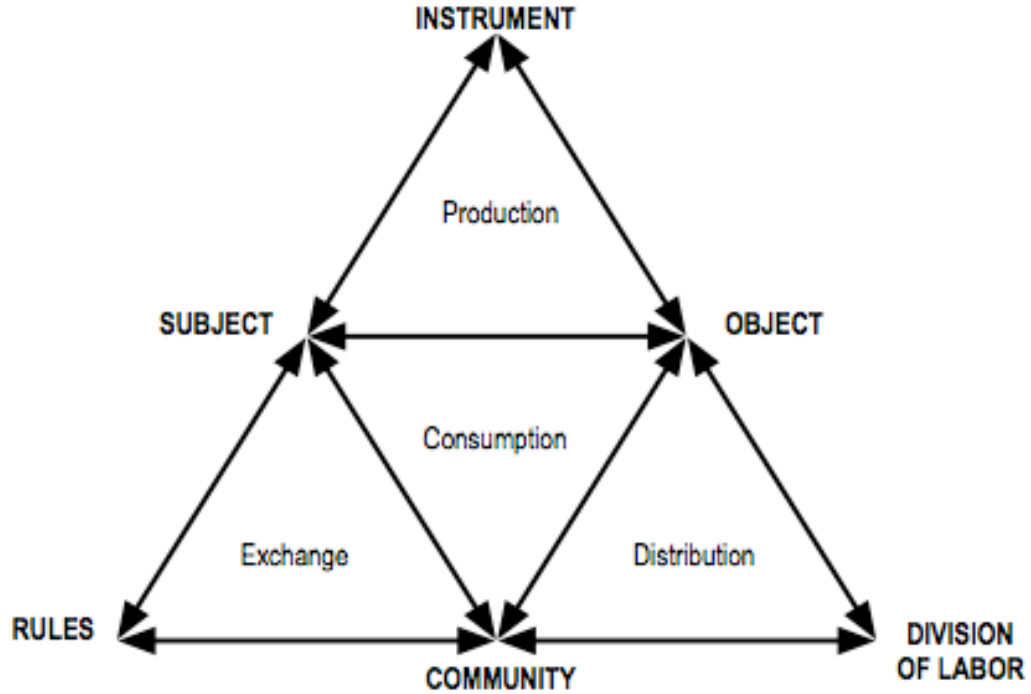


Figure 1.3: Engeström's model of a human activity system (Engeström, 1987, p. 78)

Although the diagram appears to be static, there is constant motion within and among activity systems. Activity evolves through this structure of mediated and collective human agency (Roth, 2007b). Evald Il'enkov, a Soviet philosopher, proposed that internal contradictions are the driving force of change and development in activity systems (Il'enkov, 1977). As activity systems interact with each other and exchange artifacts, outside influences can create imbalances and contradictions. Furthermore, as activity theory became universally known, the lack of a mechanism for dealing with cultural diversity became a severe limitation. Michael Cole realized that activity theory must also be inclusive of different cultures and activities. He sought to combine American emphasis on

cultural context and concrete activity systems with Soviet emphasis on mediated structure of higher psychological functions and the importance of history, political economy (Cole, 1988). This third generation cultural-historical activity theory is challenged to develop conceptual tools to understand dialogue, multiple perspectives and voices, and networks of interacting activity systems. The network is formed as activity systems exchange artifacts, such objects, texts, means of production, and people. All activity systems can be seen as part of a network of activity systems, which then constitute society (Roth, 2007b). As activity systems interact with each other and exchange artifacts, these outside influences can create imbalances and contradictions.

Contradictions are the impetus to change and can occur at different levels in the third generation activity model, within and between systems (Engeström, 1987; CAT & DWR). The inherent paradox of any activity system is that consumption necessitates production and production necessitates consumption (Jonassen, 2000). Primary, Level 1, or intra-component contradictions are those within the components of the central activity (e.g., within subjects, within rules, or within instruments) and emerge from the imbalance between production and consumption, between production and the need to control costs. The existence and identification of primary contradictions makes inter-component contradictions evident (Holt & Morris, 1993). These Level 2 or secondary contradictions appear between elements as a new element enters into the activity system from the outside. Tertiary contradictions arise when culturally more advanced objects and motives are introduced into the central activity. This is a familiar occurrence in the workplace, for

example, when new technologies or new accounting systems are introduced. Level 4 or quaternary contradictions are those that emerge between the changing central activity and its neighbouring activities in their interaction. In Nova Scotia such contradictions occur when locals using a historic access to oceanfront are confronted with new owners of the land who do not respect that right. It is the tertiary and quaternary contradictions that provide the potential for greatest learning and radical innovation to occur (Engeström, 1987).

### *Basic Principles of Cultural Historical Activity Theory*

Just as it has many names—AT or activity theory, CHAT, social-cultural psychology, cultural-historical psychology—it has no unified theory but rather common principles. In reality, it is not a theory but “a collective, artifact-mediated and object-oriented” framework for discussing, understanding, and studying human behaviour and for designing learning environments (Engeström, 2001, p. 136). As such, it is applicable in diverse fields, among them psychology, curriculum and teaching, information technology, and the workplace (see Holt & Morris, 1993; Engeström & Miettinen, 1999; Jonassen, 2000 for examples) and has been shown to be a powerful tool for revealing the structure, interactions, and communication failures in the systems studied (e.g. Engeström, 1999b). A synthesis of Cole and Engeström (1993), Cole and Levitin (1998), and Engeström (2001) suggests six principles of human activity.

1. Human development and psychological function are dependent on mediated action through culture and social interaction. This assumes a unity of consciousness and activity.
2. Culture, or social inheritance, is embodied in value-laden artifacts produced in/by goal-directed activities.
3. Cultural mediation is bidirectional, modifying both the environment and the subject.
4. Cultural artifacts are simultaneously material and symbolic. Language is the supreme tool.
5. Activity systems have multiple voices, points of view, traditions, and interests and with them, historicity. Activity systems evolve over time.
6. Structural tensions or contradictions arising from multiplicity within and among activity systems are sources for potential change, development, and transformation.

### *Critique of the CHAT Framework*

#### *Advantages.*

Recall that activity theory is not a theory but a “philosophical framework for studying different forms of human praxis as developmental processes, both individual and social levels interlinked at the same time” (Kuutti, 1996 as cited by Jonassen, 2000, p. 97). Perhaps the most positive aspect of activity theory is its ability to cope with dialectical



relationships: individual-collective, material-mental or body-mind, subject-object, biography-history, praxis- theory (Cole, 1988; Ratner, 1996). It does not treat dialectical relationships as either-or, but as interdependent and interrelating aspects of the same thing, “nonidentical expressions of the same category” (Roth & Lee, 2007, p. 195).

Individuals come to an activity such as the chemistry laboratory not as clean slates but as beings influenced with all the events and people in their lives, their beliefs, their preconceptions and their misconceptions. Their behaviour, participation, and learning in an activity are interrelated and interdependent on others members of the activity community as well as the other influences in their lives.

Along with the individual-society dialectic, activity theory also operates on three planes simultaneously: community, interpersonal or relational, and personal. These levels are interrelated; there is interplay between levels. The three levels of analysis—activity, action, and operation—can be integrated with the three planes in that object- or motive-oriented activity is carried out by the community, goal-oriented actions are carried out by the individual or the group, and conditioned operations are carried out by routinized individuals or machines (refer to Figure 1.2).

Because the researcher in the system is an active participant in the activity process, CHAT provides a method for dealing with participation and distance. The activity can be viewed from different perspectives, providing a rich, multifaceted, and perhaps contradictory understanding of the domain (Wells, 2004). New and as yet unimagined

ideas can be generated from these alternative analyses. The researcher benefits from insider knowledge and can still step back. The context of activity and individuals' experience of that context are being studied, not the individuals themselves; thus alleviating ethical concerns.

CHAT is attractive for educators because it addresses the theory-praxis dichotomy. Knowledge and practice are mutually supportive; theory without context does not encourage understanding, does not aid in problem-solving, and does not inform transfer of knowledge. "Concepts, rules, and theories that are not associated with activity have no meaning" (Jonassen, 2000, p. 109). Conscious learning occurs within the context of activity and activity requires consciousness. As Roth and Lee put it, "learning is equivalent to the mutual change of object and subject in the process of activity" (2007, p. 198).

Activity is not static but a constantly evolving complex process of individual and societal mediated goal orientation. Thus, activity theory accounts for the historicity of meaning, of value, of the artifacts in use and produced, and of the problems, tensions, conflicts, etc. Historicity links an activity to its past and to congruent activities and so activity does not occur in isolation. Intrinsic to history is context. The framework of activity accounts for not only the local context, but also the global, and political aspects of the activity system (Wardekker, 2000). Activities evolve over time within a culture (Jonassen, 2000) and activity theory itself is constantly evolving in its own activity system

(Engeström, 1993). Furthermore, the components of an activity system interact and can interchange. The functions of a component can also be changed; for example, language can be used to instigate action, to discuss action, and to generate theories. Activity theory is not mired in one time or place but is ever evolving as the activity itself evolves. Current learning research considers motivation, emotion, and identity within the activity framework (Ratner, 2000; Roth, 2007c). Clearly, its advantages make activity theory an appropriate tool to address the lack of relevance in science education (Holbrook & Rannikmae, 2007, Roth & Lee, 2004, van Aalsvoort, 2004b). This sociocultural approach shows where research is needed, especially to develop science teaching for a heterogeneous classroom with social, cultural, and linguistic diversity (Lemke, 2001).

*Disadvantages/Shortcomings.*

The very ability of activity theory to accommodate the individual  $\leftrightarrow$  societal dialectic is sometimes viewed as problematic in that CHAT ignores the subjectivity of the individual in favour of the group (Sawyer, 2002). However, such a shortcoming is perhaps more a function of the analyst using activity theory rather than the theory itself. As Roth (2004) comments:

The subject in the triangle is usually identified with an individual or group. In my view, much confusion arises from the fact that the subject is treated as coextensive with the physical boundaries of the individual or the group. But this cannot be, for the object of activity also includes its image, which is something perceived by and characteristic of the individual (p.3).

Similarly Suchman (2000) identified the problem of misinterpretation of data when researchers do not fully understand the nature of the dialectic and functional relations

between subject, tool, and object. This is more apparent in mathematical knowing when the tool is taken for a property of the person (Roth, 2003).

Tool-mediated activity of the individual in society means that the context of the activity is important. Cole (1988) suggests that perhaps conclusions can only be related locally if activity is context-specific. In his cross-cultural research, he discovered that cultural differences in cognition are domain and content-specific (Cole, 1988). Yet, context-specific sociohistorical characterization, for example, of educational practices and psychological tests, more accurately reflects reality and removes researcher bias and preconceptions. In the same article, Cole considers cultural history and the fact that change occurs over different time scales. Once development changes its time frame to longer periods, cultural development is seen as unimportant compared to changes based on political economy. Later Cole writes:

Vygotsky [1987] is often cited for his emphasis on the necessity for genetic analysis of human thought (where genetic' is construed broadly as 'historical' on different time scales: microgenetic, onto-genetic, cultural-historical genetic, and phylo-genetic). By the same token, culture does not refer solely to historically accumulated differences between relatively large human groups....In this sense, culture and cultural mediation are universal features of human life and an integral part of human development. Consequently, the process of cultural mediation can be studied in a broad range of practices within any large, demographic, culturally constituted group (Cole, 2001, p. 168).

## Methods

The teaching laboratory is a complex environment...there are interactions between students and the activity, students and the equipment, students and laboratory instructors, and students and each other...All these interactions can be viewed as occurring within the broader framework of the cognitive, affective, and psychomotor domain (Nakhleh, Polles, & Malina, 2002, p. 79).

In 1982, Hofstein and Lunetta examined research into laboratory work and concluded that studies insufficiently documented important interrelated variables in the lab environment and researchers needed to learn about these relationships if the function of the lab was to be fully realized. Twenty years later, Nakhleh et al. reiterate the intricacy of the lab environment as quoted above.

One framework of analysis that considers these variables and relationships is activity theory. Activity theory encompasses communities of practice (Wenger, 1998), distributed cognition (Salomon, 1993), and actor-network theory (Law, 1994; Law & Hassard, 1999). Activity analysis offers the advantage of spotlighting one interaction whilst keeping its connections with the entire activity system in mind. It provides a framework to examine the relationships and interactions in the laboratory environment along with elements of power, affect, and cognition. Relationships and interactions within and among activities are interrelated and interdependent; university administrative decisions impinge upon departmental activities, which in turn may have repercussions in practical work. Similarly,

laboratory mishaps or chemical use may have an impact on departmental and university policy. It is apparent then, that activity manifests on three levels concurrently: community, relational, and personal. These can be likened to Hatch & Gardner's (1993) three levels contributing to cognition: cultural, local, and personal. Using the framework of AT implies that these influences on collective and individuals' cognitions and interrelations will be considered.

Jonassen and Rohrer-Murphy (1999) suggested a series of steps for applying activity theory to constructive learning environments. Later, Jonassen (2000) drew on AT as a framework for designing student-centered learning environments, seeing in it a means to support collaboration and sharing of knowledge in the participation of student-centered activities. In his examination of secondary school chemical education, van Aalsvoort (2004b) turned to AT to address the lack of relevance of school chemistry. School versions of chemistry and chemical or chemistry-related social practices differ considerably. Activity theory grounds knowledge in social practice; citizenship is discernible through participation in social practices. This feeds directly into models of scientific literacy for responsible citizenship. Indeed, Holbrook and Rannikmaa (2007) attest that activity theory is the appropriate tool to address the lack of relevance of science education to scientific literacy. Attributes such as emotion, identity, and reflexivity contribute to activity (van Aalsvoort, 2004b; Roth, 2007a; Roth & Lee, 2007) just as they influence students' participation and learning in the lab. Furthermore, AT has been used at the tertiary level to uncover contradictions within chemistry undergraduate teaching in

order to transform teaching (Kahveci, Gilmer, & Southerland, 2008). Activity theory seeks to understand the components and influences on activity and their interrelations and interactions without trying to impose a simplified cause- and-effect relationship. For Maxwell (2004), this gives it greater validity.

CHAT analysis considers the variables in the laboratory that Hofstein and Mamlok-Naaman (2007) identified as requiring research. Analysis of the interrelationships can determine what skills and abilities are emphasized and what level of scientific literacy is supported. Identification of contradictions within the activity system provides a pathway to enhance the possibilities and depth of learning. CHAT manages dialectical relationships, for example, the individual-society dialectic—students as sums of their experiences. In addition, activity analysis considers both historicity and change; an activity system is constantly evolving yet subject to its past and influenced by the present. Researchers in various disciplines have successfully used CHAT analysis. In summary, activity theory can account for the complexity of the lab environment and the factors influencing the activities within it, thus positioning AT as a suitable framework for analysis.

In the next chapter, I investigate a typical undergraduate chemistry laboratory beginning with a thick description. I then examine this laboratory activity using CHAT in order to determine what skills and abilities are nurtured and what level of literacy is encouraged.

## **CHAPTER 2: THE TRADITIONAL LABORATORY**

This thesis argues that updating laboratory instruction corresponding to contemporary learning theory will result in more effective learning. I have detailed cultural historical activity theory, the framework for analysis, and the benchmark I use to assess improved learning. Now I describe a typical laboratory scenario and analyze the interactions to determine what learning is being modeled and rewarded.

### **A Typical Day in the Laboratory**

Practical work has been part of the science studies since science became part of the school curriculum in the late 19<sup>th</sup> century (DeBoer, 1991). Students would learn inductive thinking (in addition to the deductive thinking provided through the humanities) and develop skills in observation by carrying out independent investigations in the laboratory in the application of scientific knowledge to relevant activities in life. However, there remained, and still remains today, a tension between social relevance and intellectual understanding. The aftermath of World War II and the launch of Sputnik in 1957 changed the focus of science education to a more knowledge-based curriculum. These new courses largely designed by scientists themselves, emphasized rigor, abstract models of the natural world, and practical work that mirrored scientific work (Braund & Reiss, 2006; DeBoer, 2000). The traditional laboratory experience originates from this tradition.



The traditional laboratory ‘experiment’ requires students to follow a set procedure to (re)produce a known result, a confirmatory exercise. While some experience in these types of experiments provides an effective method for assessing expertise in analytical methods, an over-reliance on them kills imagination and interest. Consider the following exchange between two students whose lab exercise involves using a spectrophotometer to measure absorbance. The students prepare a set of standards with known concentrations and treat a solution of unknown concentration in the same manner. From the readings they produce a standard curve of absorbance versus concentration. Once they have found the absorbance of the unknown solution, they can determine its concentration by finding the point of intersection of absorbance of the unknown with the standard graph or by calculation methods once they determine the slope of the standard curve. This method has many applications and is easily normalized for field use.

Chris: Did you see Bev at the bar crawl? Man, she was gone. Oh, what’s this solution for?

Pat: We’re supposed to add it to the test tubes after we’ve added the ones in the table.

Nah, I went to the open mike night since a friend of mine was playing.

Chris: Oh, yeah, now I remember. And more to the other tubes.

Pat: It changed colour. Are we supposed to write that down?

Chris: I don’t know. We use the machine anyway and we’ll get different numbers. Then we make a graph. How did it go anyway?

Pat: Pretty good. Heard some neat music.

*Some time later. . .*

Chris: Isn't this line supposed to be straight or something? It looks like Bev at the bar.

Pat: How d'you know? You weren't there. I just connected the points. This point here is weird.

Chris: But we're supposed to find something out from the line and we can't do it unless it's straight.

Pat: Okay. I'll just ignore this weird point and the rest line up pretty good. As long as it looks right, that's all that matters. Now what do we do with it?

Chris: Don't we have one more reading?

Pat: No, they're all here. Oh, yeah, one for the solution we don't know. Maybe it's the weird one. Do you have the data? Maybe mine is mixed up.

Chris: Here's what I have. I gotta go, see you next week.

In this scenario, the two lab partners seem detached from the laboratory, following instructions blindly and unaware of the significance of the colour change, that a more intense colour is indicative of a stronger concentration. Because they neglect to write down their observations, they do not know why there is one 'stray' data point. Indeed, Pat has not labeled data completely enough to determine which readings belong to the standard curve and which data point is the absorbance for the unknown. Rather than solve their problem together, discuss the issue with other students in the lab, or speak to the instructor or TA, data are exchanged and Chris leaves the lab. Sometime before the lab write-up is due, each person will struggle to make sense of the experimental data, find a

value for the unknown, and hand in their report without understanding the concept, technique, or reason for the exercise.

Perhaps this is a familiar scenario—following a set protocol for a compulsory experiment that has a predetermined outcome. The students are not required to make any decisions, or to have any input in what data is collected, how the data is collected, or how the data is represented. They may be inattentive, simply following the instructions and leaving the lab as soon as possible. They do not exhibit any curiosity about the study; they do not repeat the experiment; they do not try anything different. What do students really think about their university course work anyway? What has happened to science laboratory investigation that leaves students so uninterested, so uncurious, and so uninvolved? What is happening in lab instruction to result in such bored students? How can teaching resulting with these attitudes promote the scientific literacy described in chapter 1?

In order to answer those questions, I will analyze the traditional laboratory through the lens of cultural historical activity theory, or CHAT. It provides a framework to identify and consider the actors involved, their interactions, the tools in use, the history, the social setting and social norms, emotions, identity, and motives within an activity, in short, the ‘stuff’ of everyday life. I examine the activity system of the undergraduate chemistry laboratory, describe each part of the activity system, and consider the interactions between them, the contradictions and assumptions. These descriptions are taken from personal experience as an instructor, from artifacts, and from the literature.

## **Analysis of the Traditional Undergraduate Chemistry Laboratory**

I begin with a general analysis of the laboratory by completing the description of the lab itself, the people in it, and their responsibilities. Then, I consider the components of the activity system and how they are interacting. This leads into a discussion of the contradictions present in the traditional laboratory, highlighting the learning (not) taking place.

### *General Description of the Undergraduate Chemistry Laboratory*

Looking more closely at the environment of the chemistry laboratory, not much has changed over the years except perhaps that the technology is more sophisticated. A general chemistry laboratory is laid out today in much the same manner as 20 to 30 years ago (Hand & Prain, 2006). In most courses, students work with the same partner for the term at long lab benches running parallel to others in the lab, with other students scattered throughout the room. They are assigned to a locker containing equipment and glassware; chemicals and extra items are placed on a central bench. Balances are available on a side bench or a small room off the lab itself. The instructor gives a short talk about the experiment, demonstrating technique if necessary, perhaps noting safety concerns and problem areas, indicating where to find what they need, and then lets them begin, everyone doing the same investigation. The discourse is generally one-way; students may be asked questions in a typical I-R-E cycle—the teacher inquires, the student responds,

and the teacher then evaluates (Bleicher, Tobin, & McRobbie, 2003) to ascertain if they have understood the procedure, or may be asked if they themselves have any questions about what was said.

During the lab period, the instructor may simply sit at the ‘front’ of the lab and expect students to come with their difficulties. Alternatively, the instructor may walk about, checking for safety violations, establishing correct procedure, or asking students what they are doing. Teaching assistants, often graduate students, will also be present as second eyes. In undergraduate institutions, upper year students serve as demonstrators.

Students follow protocols described in a purchased lab manual, often produced by the chemistry department itself and less frequently in a commercially produced lab manual. A lab schedule is presented at the beginning of the manual, followed by safety notes and then the experiments. Each experiment begins with a number, title, purpose, and a chemicals and equipment list required to complete the experiment. A short section on background information and theory often precedes the procedure. Other resources are generally unavailable in the lab, except perhaps a reference such as the CRC Handbook or Merck Index. Students bring their own textbooks, calculators, pens, paper, etc. More recently, students record their observations and data either on preprinted sheets provided or on their own as per the instructor’s/lab manual’s guidelines. This move away from full lab reports is in response to complaints of heavy workloads in science courses.

### *Components of the lab activity system*

Consider the undergraduate laboratory as the central activity of interest. Students come to university from different cultural backgrounds, with different educational background, different expectations and goals, and different beliefs. Their motives are varied: to live on their own, to fulfill parents' expectations, to discover what they really want to do, to find out what matters to them, to get an education for a job, et cetera. Yet, a class of heterogeneous individuals is expected to learn in a homogeneous manner. Tensions or contradictions become apparent in identity, language, goals, power, adherence to the scientific method, and methods of instruction.

#### *1. Subject of activity—the student.*

First year students, most at the cusp of adulthood, arrive at university with learning and coping strategies, preconceptions and expectations from earlier schooling. Perhaps unknown to them, their primary learning will be to construct their evolving identities (Chickering & Reisser, 1993; Illeris, 2002, 2004). The students in the vignette, Chris and Pat, find their social life of more interest than the material presented by the laboratory exercise. The opportunities for leisure and entertainment and for learning socially are more enticing than formal learning. Those students currently at post-secondary institutions, millennial students, have grown up with computers and the Internet, the digital technology of CDs and MP3s, and instant communication by cell phone, text

messaging, and e-mail. This generation reared with technology often has poorer reading and writing skills (Côté & Allahar, 2007).

The conversation of the students in the vignette displays limited vocabulary and is entirely lacking in scientific terminology. Scientific discourse is an impediment to understanding for students and has been one focus of research in science literacy for many years (Yore, Bisanz, & Hand, 2003). The language is dense, specific to science, and very different from colloquial English (Zhihui, 2005). In addition to learning content, students are confronted with learning the correct terminology that only gets practiced in science classes or read in scientific print. Students must learn and grasp the concepts of science without a familiar vocabulary on which to build understanding.

Customarily, in most science laboratories, knowledge is developed through observation, measurements and human reasoning. Affect—emotion and mood—, it is widely (albeit mistakenly) believed, does not enter into dispassionate scientific research. Science education ignores the affective register of identity (Bracher, 2006). Jane Roland Martin refers to John Dewey who “spent his life trying to combat the tendency of educators to divorce mind from body and reason from emotion” (Martin, 1985, p. 72).

The students are present often because the lab is compulsory. Using simple instruments of recording such as pencils and pens, their prescriptive lab manuals, and perhaps class material, these students fulfill the procedural requirements and submit a

report of their results. There is little or no attempt to situate their inquiry in context or in group discussion; rather, they work in relative isolation, having adapted to this model of school-going in order to get the grade for the credit for the degree. Like Pat and Chris in the vignette, often students fail to get involved with the task at hand; interesting and challenging ideas are for the nebulous future, after graduation. Students see this production of lab reports as isolated from other subjects, from other laboratories, from other universities, and from the world. What should be the central activity of that particular moment in students' trajectories is viewed as a hoop to be jumped through before real life can occur (Osborne, 2007). The equipment they use and the inscriptions they produce have no relevance outside of the course.

## *2. Instruments of the chemistry laboratory activity.*

The typical cartoon depiction of a laboratory shows a plethora of glassware surrounding a white-coated male scientist (Driver, Leach, Millar et al, 1996). The glassware is the first thought for tools used in the laboratory. Instruments for analysis of samples (to print out numbers or a plot) and other equipment for manipulating samples (heating, cooling, mixing, centrifuging, etc) are generally available as required. The sophistication of the equipment used will vary depending on the course, the level, and the institution, although similarities exist across institutions. These tools generally are up to date but may lack some automated features available to a research scientist. Chris and Pat are using a spectrophotometer, "the machine" as they call it, for their absorbance data but are drawing their graph by hand on paper and determining the value of the unknown from the graph.



Textbooks, reference books, lab manuals, instruction, notes, conversations, and inscriptions are the available semiotic tools. Students also bring with them tools to record: pens, pencils, paper, calculators, etc. At times, tedious operations that are easily done by computer software are done manually. Although Chris knows that the drawn graph must be a straight line, Pat does not appear to be sufficiently familiar with these types of inscriptions to realize that points are not connected but rather that the best fit produces the line. They do not refer to their lab manual, their textbook, or their class notes to determine the error in their graph, assuming simply that the stray data point was the value for the unknown. They either do not have or are unaware of graphing calculators to check the soundness of their data.

### *3. Object of activity.*

The purpose of the laboratory activity system depends largely on whose perspective one takes. For the subject, the student, generally the course is a prerequisite or required for a degree; the object is to pass the course in order to get the necessary credits to qualify for the degree, the end goal. This suggests that the main motivation of students is passing rather than learning. The goal of the students in the vignette appears to be to complete the experiment as soon as possible in order to take part in other activities. Talk about the lab itself is secondary to exchanging information about their social life. The role of the laboratory instructor is perhaps threefold: to develop students' competence in lab manipulations, to develop students' familiarity with chemicals and their reactions, and to illustrate some theory or reaction(s) presented in class. The professor, who often is not

responsible for lab teaching, aims to impart knowledge and ‘create’ the next generation of scientists through reproduction of the familiar culture, or, as is often the case in smaller institutions, impart sufficient chemistry literacy so that student can pursue education in related fields. Tensions are immediately obvious.

#### *4. Other components of laboratory activity.*

The students must abide by the rules of the institution for the degree requirements, the rules of the department for progression through the program, and the rules of the laboratory for safe practice and social civility. Both the institution and the department are bound by regulations set out by credentializing bodies. Finally the instructor is answerable to the department and the safety committee. The students fulfill the minimum requirements of attending the lab, following the procedure and submitting a report of their results.

The traditional lab functions as a class of separate individuals, discouraging community interaction. Partners may or may not exchange ideas and answers. Experiments are completed individually or in pairs, contributing to the separation. Chris and Pat do not converse with their bench mates, compare their data, or discuss any problems. It almost appears as though they are the only individuals in the laboratory. Students see the instructor as a source of ready answers rather than a resource to develop their understanding. The technician in the stock room often provides a sympathetic ear as well as knowledge of the experiments performed. Since the role of the professor in the

laboratory varies greatly among institutions, professors are sometimes not viewed as members of the laboratory community. This serves to further emphasize the division of labour in science learning.

Labour divides both vertically and horizontally. Traditional instruction presents a hierarchy congruent with a hierarchy of knowledge: the professor at the top, followed by the instructor, the stock room technician, and finally the students. Students working in pairs often divide their labour between note-taker and 'doer', between the watcher and the hands-on worker, between the 'smart one' and the one needing help. Friends of similar skill and aptitude will more equitably work together. I discuss the perturbations or contradictions that arise within and among these components of subject, object, goal, community, rules, and division of labour in the following section.

### *Contradictions in the lab activity system*

Engeström (1987) voiced his concerns about the contradictions in school-going activity in capitalist systems (see figure 2.1). Unfortunately those contradictions he identified remain relevant today and are apparent in the lab activity system

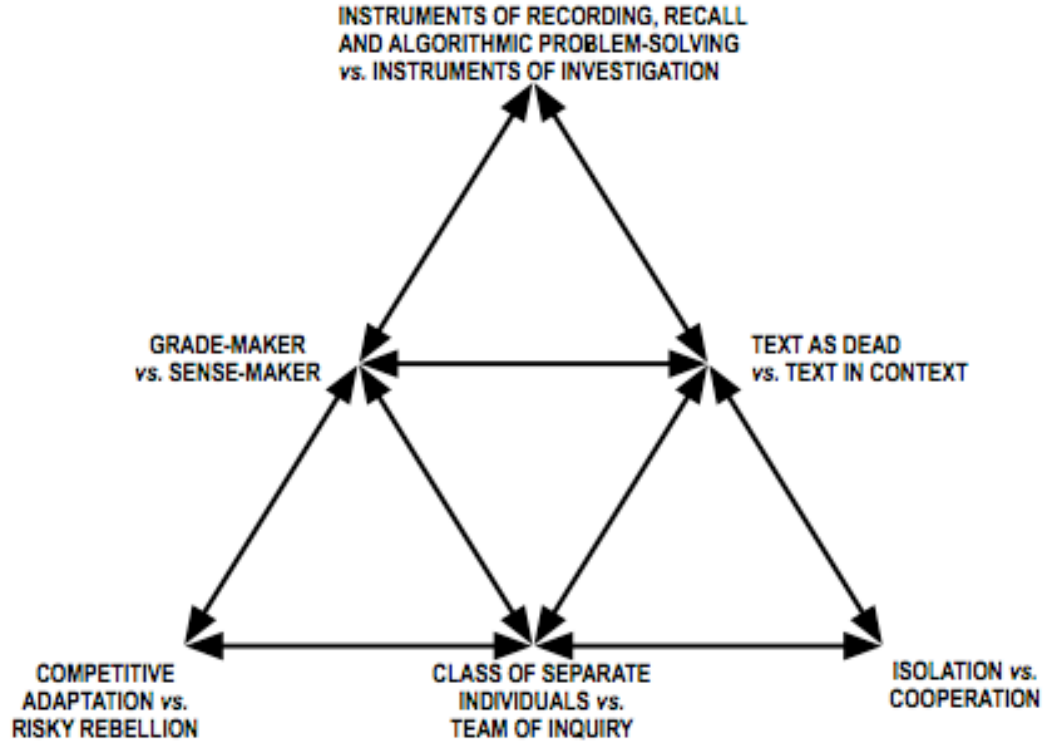


Figure 2.1 Primary contradictions in school-going activity (Engeström, 1987, Figure 2.8).

Students enroll in courses having met prerequisites. Yet there is a contradiction between what they know and what they ought to know (Roth, 2004). This is not limited to subject knowledge, but includes English language and mathematical knowledge as well. Millennial students often have poorer vocabulary, grammar, and writing skills, attributed to their use of abbreviated text messaging (Côté & Allahar, 2007). Despite the prerequisite of mathematics, students' familiarity with basic graphing and algebraic manipulations cannot be assumed and instructors must give a tutorial on X-Y plots in lab.

Many students are grade-makers rather than sense-makers as identified by Engeström. Their main goal is learning to get the credit; learning for understanding may or may not occur (Côté, & Allahar, 2007). Unfortunately, the instruments of the laboratory as depicted in the vignette support this goal. Chris and Pat record data and follow the procedure for producing a graph and finding the value of the unknown. They are not required to investigate a problem and arrive at a solution. By these simplifications of cookbook labs, mainstream educational systems favor the exchange value of school grades over the use value (Lave & Wenger, 1991). This leads to reproduction of the text as success in the game of school.

Although students are members of a class, individual work is preferred over group inquiry. Students have been encultured to work alone. This was apparent in the vignette when Chris left Pat with his data, students writing individual reports in isolation rather than cooperation. School-going is not their primary activity but only one of several, which vie for their attention and concentration. Conflicts and contradicting expectations of the various communities in which an individual participates can impede school learning. In the vignette, the students discussed their social life rather than the work at hand; university has become the means to a better social life.

The goals of the students and the aims of a course are often contradictory. In smaller institutions, chemistry majors, science majors, and other students are often in the same class and laboratory. Students may be enrolled in chemistry only because it is compulsory for their field of study, yet the aims of the course may be to enable further

study in chemistry. Tensions arise between students who just want the credit and instructors who want to ensure adequate preparation and sufficient standards.

A contradiction exists also between the goals of the course and the actual reality of the classes and labs. Most chemistry courses aspire to students being able to apply the foundations and theories of chemistry to the real world yet provide esoteric examples that do not connect with anything the student knows. Advanced courses may emphasize higher cognitive skills such as concept knowledge, problem-solving and critical thinking, yet still rely on conventional labs. The lab reports are written in a format that suggests a rigorous approach or “scientific method” that has no reality. One function of experimental work is to give experience in problem solving, yet the problem/purpose and the protocol for its solution are given in the lab manual. Furthermore, assessment is often based on written reports and the results obtained rather than on lab deportment, manipulative skills, and approaches to techniques for problem-solving. Chris and Pat know this, and know that the value given to lab work is minor compared class work. For them, the mark allotted to the laboratory portion of a course does not warrant the amount of time required to do in-depth work. The activity in which Chris and Pat are engaged bears little resemblance to the academic reasons for practical work. “When students are isolated from their goals, intentions, tools and certain social relations, they in fact look as if they were disabled” (Roth & Barton, 2004, p. 132).

The imbalance between production and consumption is present at all levels in the university, the main contradiction being between high levels of quality that require more expensive interactive learning components and cost recovery. A large lab with one instructor and several teaching assistants may be more cost effective in terms of salaries but less in terms of safety. As student numbers increase, the instructor has less time to converse with students like Chris and Pat to direct their attention to the importance and extensive applications of this particular method of analysis. Familiarization with computer-assisted instrumentation is assumed for graduates of chemistry but the costs involved may be prohibitive for small institutions. Pat and Chris must produce their own graph and deduce the unknown result, an exercise that can easily be automated. Familiarization with certain analytical techniques and their applications is also a *de facto* requirement. The instructor must be able to assess students' skill by some measurable means and resorts to verification experiments in order to do this. Thus arises the contradiction between manually produced results and automated results, the latter more likely in industry. With automated data display (e.g., of tables and graphs), students' focus would be on the instrumentation rather than the concepts being illustrated. And without knowledge of the principles, students would not understand how the mechanized version operates or how to use the data generated.

Contradictions exist between the object and the means of instruction. While the goal of the lab may be to support students as independent problem solvers and thinkers, the artifacts in use largely support rote work. Experiments in the lab manual often do not

change from year to year. Students realize that the actual object of learning is comprehension and memorization. To that end, they will take the most expedient and least demanding approach to learning (Jonassen, 2000). Chris and Pat did the minimum amount of work to complete the data gathering, not bothering to verify that their 'weird' data point is the absorbance of the unknown. The meaning students interpret from the lab exercises is not critical thinking but reproduction and verification of predetermined results. The tools and artifacts generally do not support collaboration and discussion. Activities must be consistent with outcomes; "the contradiction between real and expected learning outcomes may represent the greatest impediment to learning" (Jonassen, 2000, p. 118). If indeed the goal of practical work is to enculture students in doing chemistry, in knowing about chemistry, and in scientific literacy, the traditional laboratory fails. What theories of learning are being reproduced in the undergraduate chemistry laboratory to lead to this situation? I discuss them, as well as attributes of the individual such as identity and affect in the next chapter.



## CHAPTER 3: TRADITIONAL LEARNING

The foregoing description of the undergraduate chemistry laboratory raises an important question: Why rely on costly laboratory instruction if the learning outcomes appear so uncertain? To answer this, in the following, I explore the history of science education focusing on tertiary institutions and the genesis of lab instruction to understand more clearly the learning theory that formed the basis of lab instruction and the teaching of science in general. Has the theoretical basis changed with new knowledge? What assumptions does this theory make about the learner and what characteristics of individuals does it ignore? Can this theoretical foray account for the outcome of the lab described in chapter 2? I begin this chapter with a brief history of lab instruction and its theoretical roots. I follow with a description, functions and focus of the traditional lab and the lab manuals used. This leads naturally to the students, their identity and how they view science and laboratory work. With all of this in hand, I then identify the learning theories that, I argue, rest at the very crux of dominant approaches to laboratory instruction. It is these learning theories, I suggest, that ultimately have led to the disappointing outcome in student engagement and learning.

## A Brief History of Chemistry Laboratory Education

Science was first taught as natural philosophy, reaching back to the Aristotle (382 BCE-322 BCE). In the West, the emergence of universities in the late twelfth century replaced the cathedral schools as centers of learning, with those at Paris, Bologna, and Oxford being the most prominent (Grant, 1971). By the mid-thirteenth century, natural sciences were required for the Master of Arts degree (Grant, 1971). Francis Bacon (1561-1626) first published *The Advancement of Learning* in 1605, proposing a new methodological approach to supplant the Aristotelian style. Isaac Newton's (1642-1727) *Principia* or *Mathematical Principles of Natural Philosophy* published around 1687 (the third edition, greatly revised, was published just before his death in 1727) is still regarded as the most important book on natural philosophy of that period. By the time of Antoine Laurent Lavoisier (1743-1794) [basic table of 'elements' and three states of matter: solid, liquid and gas] and Joseph Priestley (1733-1804) [discoverer of oxygen], the foundations of modern chemistry were laid. Education in the classical languages and literature was no longer sufficient in the age of scientific advances and the subsequent erosion of dogma. Science then became taught as a field of objective empirical knowledge rather than a philosophical discourse.

At the beginning of the 19<sup>th</sup> century, the domain of the chemistry laboratory was largely restricted to scientists who had private laboratories for their own research but not for teaching, apothecaries who were guild-based, and entrepreneurs in the industrial production of items such as soda, potash, gunpowder, soap, paints, and dyes. From 1617

with the permanent arrival of the apothecary Louis Hébert in Quebec to about 1880, “chemist” in Canada actually meant apothecary (Tory, 1939). Scientists like the Swede, Berzelius (1779-1848) would allow carefully selected guests to visit in their private laboratories from time to time but no regular instruction was involved (Rocke, 1993). However, by 1850, most institutions of higher education had some practical instruction if it not associated with a scientist, associated with schools of medicine (Harris, 1976).

Smeaton (1954) credits the first known practical course to be that of M.V. Lomonosov (1711-1765), professor of chemistry at the Academy of Sciences of St. Petersburg, offering lab instruction from 1752-1756 as part of his course. It appears that the practical work was carried out in his small laboratory, so very few students had this opportunity. In 1735, The Academy of Mining founded in what is now Banská Stianvnica, Czechoslovakia (formerly Selmecebánya, Hungary) offered practical chemistry as part of its program (Byrne, 1969). Nicolaus von Jacquin (1727-1817) gave a public course in chemistry and mineralogy there in 1764. It is quite possible that by 1779 practical chemistry also was taught in Vienna and from about 1780 at the Ecole du Génie Militaire, although records do not explicitly mention students working in the laboratory (Smeaton, 1954).

The Ecole Polytechnique, Paris, opened in December 1794 with ambitious plans for twenty laboratories for students’ use. Chemistry instruction began the following April (Smeaton, 1954). Initially, constructing apparatus and preparing materials occupied lab

time. Later, students repeated class demonstrations, investigated properties of chemicals they had made, and occasionally obtained industrial and research experience. Cost-cutting measures from 1797-1799 reduced staff and severely limited lab time. At this time, however, student interest in experimental work was poor. In 1806, a revised syllabus of experiments was adapted to relate to the lecture courses as much as possible and to give students practice in different techniques. Practical work in chemistry still appears to have been taught as late as 1816 (Byrne, 1969). Professors such as Gay-Lussac assured the teaching of chemistry at the Ecole and influenced other scientists. For example, after working in Gay-Lussac's lab, Liebig set up a similar laboratory in Germany (Levere, 2001; Morrell, 1972).

Friedrich Stromeyer set up the first German teaching lab at the University of Göttingen in 1806 (Lockemann & Oesper, 1953), feeling strongly that students must do practical work in order to really learn chemistry. Johann N. Fuchs, professor of chemistry and mineralogy at Landshut may have had teaching labs as early as 1807, but certainly by 1820 when he began a course in analytical chemistry (Prandtl, 1951). From 1811, the University of Jena under J.W. Fischer offered chemical lab instruction (Lockemann & Oesper, 1953). From 1820 on, J.W. Döbereiner held a practical course at Jena (Prandtl, 1950) initially in his laboratory. In the fall of 1824, Justus von Liebig established a laboratory-based pharmaceutical-chemical institute at the University of Giessen (Rocke, 1993). Liebig's students carried out chemical analysis on known substances to learn the processes and later advanced to analysis of new substances. This small university became

world-renowned for its practical training and research facilities (Good, 1936). Liebig wrote:

Chemical laboratories in which instruction in chemical analysis was imparted, existed nowhere at that time. What passed by that name were more like kitchens filled with all sorts of furnaces and utensils for the carrying out of metallurgical and pharmaceutical processes. No one really understood how to teach it. (Liebig, 1861, cited by Byrne, 1969, p. 205).

In 1835, the university provided funded laboratory space with a separate balance room, the prototype of all teaching laboratories, to Liebig (Oesper, 1927). This was a marked departure from other labs whose expenses came out of the scientists' own funds. Initially, practical work was part of medicine and pharmacy, and then became important to prepare students in agriculture, industry and research; lab work for all began much later.

The teaching of chemistry was firmly established in Scotland but not so in England. Thomas Thomson is credited with establishing the first teaching chemistry lab in the British Isles at the University of Edinburgh in 1807 and later, in 1819, at the University of Glasgow (Morrell, 1969, 1972). Chemistry was taught at English universities but mostly as part of medical education and there is no evidence of practical work at Oxford or Cambridge (Byrne, 1969). Indeed, the first science courses at the universities of Oxford and Cambridge did not appear until 1869 (Warrington & Nicholls, 1949). The founding of London University (University College) in 1827 changed the insular attitudes. In 1845, it even officially recognized and supported practical teaching with a chair of practical chemistry and a new laboratory (Byrne, 1969). The Mechanics' Institution also provided

practical training at their larger schools (Byrne, 1969). As more scientists experienced Liebig's or Thomson's lab, practical classes became more widespread.

Université Laval, the oldest educational institution in Canada, originated in le Grand Séminaire de Québec founded in 1663 by Monseigneur François de Laval (Harris, 1976). Although chemistry was first taught here in 1720 (Warrington & Nicholls, 1949) largely for agriculture, its school of chemistry did not open until 200 years later (Rabkin & Lloyd, 1984). The oldest institution of tertiary education in the British Empire overseas, the University of King's College, was founded in Windsor NS in 1789 and was granted a university charter in 1802 (Harris, 1976; Warrington & Nicholls, 1949). Chemistry was one of the required courses in science as part of an arts degree; however, it is uncertain whether any practical instruction in chemistry was available to students. The University of King's College moved to the Dalhousie campus in Halifax in 1930 and ceded all science teaching to Dalhousie after over 100 years of its instruction. Chemistry was taught at Dalhousie University in 1863 and by 1880, Dalhousie University's faculty of science had initiated a 4-year B.Sc. that included laboratory work in the 2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup> years (Dalhousie University, n.d.). Laboratories for chemistry, geology and mineralogy, biology, and physics were established at the University of Toronto in 1878 and practical work became an integral part of science courses from that time (Harris, 1976). Chemistry at McGill University began in the medical school many years before it was recognized as its own field of study. The Medical Faculty initiated a practical course in chemistry in 1863. Arts students petitioned the university for a similar course in 1884 (Warrington & Nicholls, 1949). By 1891, practical chemistry was taught as a specialty of engineering with proper

lab facilities provided in the Macdonald Chemistry and Mining Building in 1989.

Government and church both played a large role in the establishment of higher education in Canada.

In contrast, the establishment of RPI—Rensselaer Polytechnic Institute—differed greatly from the institutions discussed above. Still in existence today, it was founded in 1824

“for the purpose of instructing persons, who may choose to apply themselves, in the application of science to the common purposes of life. My principal object is, to qualify teachers for instructing the sons and daughters of farmers and mechanics by lectures or otherwise, in the application of experimental chemistry, philosophy, and natural history, to agriculture, domestic economy, the arts, and manufactures” (Van Rensselaer, 1824).

A more familiar school, MIT (Massachusetts Institute of Technology), was incorporated in 1861 specifically to provide relevant education for an increasingly industrialized world.

Teaching laboratories provided experience in research and real-world problems.

From the foregoing, it is evident that laboratory instruction was initiated first for industrial applications, especially in mining, and then in medical chemistry, which later grew to include pharmacy. Separation of the various subdivisions of chemistry with their own laboratories occurred later—the biochemistry department at University of Toronto was not formally in place until 1907 (Warrington & Newbold, 1970) and that at McGill until 1920 (McGill University). By 1900, laboratories were well established in universities,

albeit merely adequate in the small institutions, good in most others, and very good at the larger universities of McGill, Queen's, and Toronto (Harris, 1976).

In answer to increased industrialization, schools began also to teach science<sup>1</sup>. The rationale for its inclusion was that the addition of science to the curriculum would develop inductive reasoning skills, mental discipline, and independent judgment skills. Natural philosophy was slow to be introduced in Canada partly due to few teachers possessing the necessary training to teach any science whatsoever. Upper Canada Academy offered chemistry for the first time in Ontario in 1836, but by 1850, only three percent of Ontario schools included any science instruction. When available, instruction was simply lecturing and learning was by memorization. By the 1870s, teacher demonstration had begun in larger schools, but it was not until 1900 that chemistry pupils commonly performed practical work as part of the curriculum in chemistry; however, equipping schools in rural areas did not occur until much later. The next fifty years saw no fundamental changes except in bringing courses up to date and improving laboratories (Warrington & Nicholls, 1949).

In the United States, Thomas Huxley passionately supported lab instruction so students could study natural phenomena directly. Students would develop skills in observation as well as in inductive reasoning. In the early 1900s, the Committee of Ten was formed in the U.S. to agree on uniform college entrance subject requirements,

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<sup>1</sup> The history summarized here is taken largely from G.E. DeBoer (1991). *A History of Ideas in Science Education: Implications for Practice*. New York: Teachers College Press.



especially in science, in essence deciding the curriculum of high schools. There was no question that the laboratory was essential to science learning. However, the purpose of the lab was repeatedly questioned, both in the US and Canada. Consequently, the focus of laboratory instruction alternated between conceptual knowledge and either social or economic relevance. For example, military and economic utility, important in the 1940s and early 1950s, was followed by a return to the basic principles of chemistry. Currently, environmental issues have become central and the function of the chemistry lab is perhaps best described as socio-environmental. How chemistry was taught fluctuated between fact-oriented and discovery or inquiry-oriented. Overall, however, the emphasis on practical work is the science content rather than experimental design or the collection, analysis and interpretation of data (Abrahams & Miller, 2007).

### **Functions and Focus of Laboratory Instruction**

The first chemistry lab instruction occurred in private laboratories, but these labs functioned more like apprenticeship programs and the assistants were furthering the research of the owner. These first teaching labs produced well-trained technicians who could further the knowledge of elements as they were discovered and do reliable chemical analysis for empirical formulae (Elliott, Stewart, & Lagowski, 2008). The teaching of chemistry was systematically developed around the laboratory method (Whitman, 1898) and by 1900, universities offered equipped labs as part of chemistry courses. Professors were very much involved in this practical work and would have bright students assisting in

these endeavours (Smeaton, 1954). The influence of the German model was very strong and many Canadian and American chemists traveled to Giessen or Göttingen to learn the most recent advances in lab methods (Whitman, 1898; Warrington & Nicholls, 1949). German universities provided industrial training by instruction in research. When American chemists returned to the States, they introduced the German system to their “universities,” and institutions not taking up this system retained the title “colleges” (Tory, 1939). Research was for graduate students. In Canada however, William Herbert Pike<sup>2</sup> instigated instruction in research to fourth-year students in honours chemistry (Tory, 1939) creating a distinction between American and Canadian universities. The lab emphasis for those students was thus on research rather than on everyday applications, an emphasis that trickled down to introductory chemistry courses throughout the degree.

As institutions grew larger, the responsibility for overseeing laboratories went to senior instructors so that professors could concentrate on their own research (Boud et al, 1986). Daniel Domin (1999b) reviewed laboratory teaching and describes four instruction styles: expository, enquiry, discovery, and problem-based. The traditional lab fits in the first category. Traditional labs go by other monikers: didactic, recipe-style, expository, structured, cookbook, controlled, and convergent. Most experiments are controlled, even at the tertiary level (Atkinson, 1990). These remain the most prevalent (Lloyd, 1992; Meester & Maskill, 1993) because they maximize the quantity of practical work and quality of results for inexperienced students (Garratt, 1997). Experiments are primarily

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<sup>2</sup> William Herbert Pike (1851-1915), second holder of the Chair of Chemistry at University of Toronto after Henry Holmes Croft (1820-1883) who was the first appointed professorship in chemistry in Canada, from 1842-1879.

verification of laws, principles, concepts, and facts taught in class, designed with scientific content rather than scientific process orientation (Matson & Parsons, 1998). Students are given the procedure, often foolproof after many years of revision, and are expected to get the “right” answer (Berry, Mulhali, Gunstone et al, 1999). After many years of cookbook labs, students tend not to prepare before coming to lab, reading the manual just before class or as they follow the procedure. Students do not even need to think about the sequence of tasks required for the investigation. As was evident with Chris and Pat in the scenario, students can complete the experiment and write the report without really thinking or understanding about the experiment itself and the theoretical concepts behind it. The student’s sole responsibility is to be there and carry out the experiment; the instructor is responsible for the method, chemicals and equipment, and safety. Thus students feel no ownership for their work and can become detached as Chris and Pat in the scenario.

Laboratory training covers a variety of purposes. Initially, it was to prepare students for careers in industrial labs (especially mining, potash, soap, and dyes) or as apothecaries. As subject areas divided into specialties, university training increasingly prepared students for academia rather than industry. Historically and culturally, chemists believe that lab work is necessary in order to understand chemistry. Chemists require familiarity with laboratory techniques, and experimental design, as well as skills in data interpretation, summarizing research findings and writing scientific reports (Clow, 1998). Sutton (1985) differentiated between the aims and the objectives of the lab: the aims are general statements on what

the instructor intends to achieve whereas the objectives are specific statements on what the student should be able to do as a result of lab work. In accordance with Johnstone and Al-Shuali (2001), I will use the same demarcation here. Many aims are attached to practical work, often with little thought into what kind of work is needed to meet those aims. The most common (and oldest) reasons given by Kirschner & Huisman (1998) for the traditional lab are:

- To illustrate theory, laws, concepts, and principles taught in class.
- To enhance students' learning, to make learning meaningful.
- To gain experience with natural phenomena.

Interestingly, investigative skills are missing in this list. However the cookbook lab generally fails to fulfill even this abbreviated list of goals. In their talks, instructors often give great attention to the procedure (its possible pitfalls and safety concerns) and the computations necessary for the report and little if any time on what students are to learn by carrying out the experiment. Perhaps it is assumed that students have the necessary theoretical background from their lectures. Hodson (1988) argues that theory and practice are interrelated: experiments assist theory building and theory determines what kinds of experiments can be performed. If the instructor does not make the link between theory and practice, neither will the students (Taber, 2000). The students naturally hear what is emphasized and follow suit. A review of the literature by Kirschner and Meester (1988) revealed the following criticisms from students and staff:

- Limited learning for the amount of time and effort invested in lab work.

- Many students can neither understand nor describe the processes and techniques used earlier.
- Too much time is wasted in trivial and verification procedures.
- Lab exercises often give or require an overload of information and overwhelm the student, especially in non-trivial experiments. As Hodson (1990) explains, Attempting to master a piece of apparatus or technique for the first time (appreciating what it does, learning how to use it, recognizing when the results can be accepted and when they are suspect, and so on) whilst attending to other aspects of the experiment—and maybe encountering certain concepts for the first time, as well—is too much to cope with simultaneously (Hodson, 1990, p. 36).
- Students almost never have the opportunity to watch a scientist execute and experiment.
- Assessment and feedback of lab work is often inadequate.
- Experiments are often seen as isolated, unconnected, one-shot exercises.

These criticisms make it evident that the recipe style lab meets none of the three most common aims for practical work. In addition, McGarvey (2004) finds that students are unclear of the aims of practical work and uncertain as to what the results mean or how they pertain to theory learned in class. This is not unexpected considering that one lab exercise may introduce a new method, illustrate a concept taught in class, demand data collection and production of inscriptions, and use an example unfamiliar to students to accomplish this all.

Then what of the objectives of the chemistry laboratory? The objectives of the laboratory are seldom identified (Meester & Maskill, 1993, 1995). What students really learn are manipulative skills, collection, treatment and interpretation of data, and standard procedures such as filtration and distillation. The traditional lab neglects to develop science investigative skills (Garnett & Garnett, 1995). Students do not identify problems, formulate hypotheses, or design procedures/experiments. There is insufficient discussion of the underlying assumptions made and the limitations of the experiment. Along with this, interpretation, discussion and analysis are weak points when the object of the experiment is simply data acquisition (Hackling & Garnett, 1995). Students either do not have the time or are too overloaded with information to consolidate the material, the results, and the theory (Winberg & Berg, 2007). With little to no attention given to fostering scientific attitudes such as objectivity, critical-mindedness, skepticism, willingness to consider evidence, and development of argument, students do not develop confidence in their abilities. Lastly, the cookbook lab experience leaves students with a false impression of the scientific enterprise as a solo, predictable, static task rather than an on-going, interactive process integrated with theory and intuition (McComas, 1998).

### *Assessment*

Historically the science of chemistry evolved in the laboratory. However, today chemistry instruction involves both a lecture and a laboratory component. From the foregoing discussion of the functions of the undergraduate laboratory, it is apparent that the lab

curriculum still attempts to fulfill cognitive, manipulative, and procedural learning. However, it is difficult to evaluate student performance in the lab in a consistent, reliable, and fair manner without clearly defined learning outcomes. Assessment for practical work is largely based on written reports and rarely includes a component for students' actual abilities and approaches in the laboratory (Hofstein & Lunetta, 1982; Meester & Maskill, 1993). Reports are prepared in a set format, according to the notion of a "scientific method" with a purpose or hypothesis, procedure, data and results, and discussion. Because students are often performing a different procedure every time they go into the lab, they have little time to consolidate the concepts and do poorly at evaluation and interpretation of the results (Johnstone & Letton, 1990, 1991). Furthermore, the marks obtained for practical work are minor compared to the time and effort required by the students. Students glance at the mark and never look at the report again, rarely bothering even to read comments and losing the opportunity to improve their learning. The enclosure of data sheets within lab manuals further discourages any synthesis of learning, ensures the students collect the correct data, and simplifies marking with standard presentation. Performance of the same experiments in consecutive years easily leads to plagiarism and difficulties in adequately assessing practical work.

### **Survey of Laboratory Manuals**

The history of lab instruction indicates a focus on chemical analysis whether for industry or research. Consequently, laboratory manuals became compendia of these methods and

practical work the site for additional learning goals. The brief survey of laboratory goals above shows that the functions and objectives of the laboratory are numerous and ill-defined. A survey of laboratory manuals used in tertiary institutions will confirm whether this lack of focus is apparent in the manuals in use as well. Furthermore, an examination of laboratory manuals reveals the kind of learning promoted by them and whether they contribute to the detachment of students like Chris and Pat in the scenario presented.

Most lab manuals contain an introduction to the concepts and other relevant background information for the experiment, a detailed stepwise procedure, prepared data sheets to record results, and pre-lab and/or post-lab questions designed to facilitate conceptual development. Manual protocols specify what data students are to collect and how they are to collect and analyze it order to verify the truth already explained to them by the instructor (Finster, 1991). Most professors argue that conceptual development is the most important aim of the laboratory, yet instructors spend the most time teaching skills so that the data required to underline the concept can be obtained. This leaves very little time if any, for students to actually think about the scientific principles being applied. They become so intent on following the procedure and obtaining the correct results that they forget the concepts being illustrated. Students try to complete the data table and finish the lab as quickly as possible (Hart et al, 2000).

Meester & Maskill (1993, 1995) analyzed first-year manuals from seventeen universities in England and Wales and concluded that practical work in those institutions was still heavily based on the traditional recipe style. In Domin's (1999a) content analysis



of ten American general chemistry lab manuals for three chemical principles, the lone in-house manual produced by the University of Wisconsin-Madison consistently promoted higher-order cognition (i.e. analysis, synthesis, and evaluation). Only the newer commercially produced manuals would sometimes possess activities for cognitive growth beyond knowledge, comprehension, and application. “Laboratory experiences of undergraduates tend to be verification experiments, with known results, or are designed to teach techniques rather than investigate processes” (Matson & Parsons, 1998). A survey of lab courses at American colleges and universities indicated that 91% followed expository experiments with a deductive approach in which lab data verified or confirmed concepts (The Chemical Education Group, 1997). Inquiry style laboratories were identified only by about 8% of the institutions. This is reflected by the manuals in use: over half (60%) using internally produced lab manuals, and 29% using commercially available manuals.

Laboratory manuals used at my institution over the past 25 years have been composed largely of prescriptive experiments. Manuals used in general chemistry contain standard well-known exercises almost guaranteed to produce expected results. Introductory courses in organic, analytical, and inorganic chemistry and biochemistry are similarly scripted for their course material. Even though a neighbouring institution has revamped their general chemistry course, the experiments in their lab manual are designed in the same manner. Gail Horowitz remarks, “The problem with asking students to follow recipes is not in giving students procedures to follow, but in giving them dumbed-down procedures in which no thinking is required” (Horowitz, 2008).

## **Other factors Influencing Science Learning**

The Millennial generation presents different attitudes than the generations prior to them. They feel they must obtain a university education for success, yet they are studying less than ever and working more hours off campus (Wilson, 2004). Neil Howe and William Strauss (2000) list core personality traits of millennial students as sheltered, special, confident yet conventional, team oriented, achieving, and pressured to perform. Their identity influences their expectations of university and their learning in that milieu.

### *Identity and the Language of Science*

Science educators have come to realize the importance of identity formation to understanding learning. Penuel and Wertsch write: “ Identity formation must be viewed as shaped by and shaping forms of action, involving complex interplay among cultural tools employed in the action, the sociocultural and institutional context of the action, and the purposes embedded in the action” (1995, p. 84). Thus identity is not a stable entity but is one of the outcomes of participation in ongoing activity. If in their school going activity students produce and reproduce their personal and social identities in the relevant community (Engeström, 1987), then the reluctance of Chris and Pat in the vignette to become absorbed in the lab exercise implies that ‘chemist’ is not part of their identity.

In addition, learning the language of chemistry may also imperil students’ identity outside of school (Brown, 2006; Smardon, 2004). Language cues identity. Students from

different ethnic groups bring different values, which may be in conflict with those of the school, and assimilation of school language may be seen as a denial of their culture and family. Furthermore, the political and social implications of science discourse form additional barriers to ethnic minorities (Brown, 2006). The language of school and of science is white, Eurocentric, middle-class, and patriarchic. Vulnerable students have difficulty straddling these two cultures and identities.

Bracher (2006) considers three registers or routes in which identity is enacted: linguistically, emotionally, and through images. Consider the linguistic route. Scientific discourse is an impediment to understanding for students and has been one focus of research in science literacy for many years (Yore, Bisanz, & Hand, 2003). The language is dense, specific to science, and very different from colloquial English (Zhihui, 2005). Furthermore, confusion arises from an incomplete understanding of terms, especially those that have other meanings in the everyday world; for example, words such as volatile and variable (Johnstone, 1997). In addition to learning content, students are confronted with learning the correct terminology that only gets practiced in science classes or read in scientific print. Depending on the students' facility with the language of chemistry, semiotic tools—textbooks, class notes, and manuals—may or may not be helpful. Students must build links between the vernacular and their referents in science (Prain, 2006).

Students must learn and grasp the concepts of science without a familiar vocabulary on which to build understanding. If these concepts and meanings cannot be

related to experience, they cannot become part of the linguistic identity of the student (Geijsel & Meijers, 2005). Both Jay Lemke and Wolffe-Michael Roth have written books on communication in the science classroom. Lemke (1990) stresses the importance of teaching students how to use the language of science and advocates opportunities for students to practice science discourse—speaking, thinking and writing—a discourse that would more closely resemble that of scientists rather than simply I-R-E- sequences. Roth (2005) takes a different view of language in science, seeing it as a dialectic relation between individual talk and collective language, between individual ideas and collective representations. Students learn the peculiar language of science with increasing investigations in the science milieu (Roth, 2005).

Kuhn (1993) goes further than Lemke to say that scientific theory is built on argument and students must therefore develop this type of science thinking in their activities. However current pedagogical practices do not support argument skills (Driver, Newton & Osborne, 2000). The lack of time to cover the curriculum in order to successfully write exams prevents any such diversions. Bleicher, Tobin and McRobbie (2003) write, “Students were . . . almost always supplying simple factual information. . . [and] were provided few opportunities to grapple with the factual knowledge and try to make conceptual connections. Nor were they provided opportunities to present alternative hypotheses to explain the phenomenon under discussion” (p. 334). Although difficulties may arise with their use, Coll et al (2005) show that models and analogies can help explain abstract concepts as learners form mental models until such time as the language no

longer forms a barrier to understanding. With increasing experience in laboratory group work and with careful facilitation by the instructor, students gradually include more correct terminology in their conversations and discussions and gradually include chemistry as an identifier to student.

### *Student Attitudes and Affect*

Students also enact their identity through the emotional register yet science is taught as neutral. While Descartes did much to further modern science, he also emphasized the mind/body split. Objectivity became associated with maleness and reason, with rational non-emotional scientific thought as opposed to irrational emotional femininity (Alsop, 2005; Brickhouse, 2001). Typically, scientific reports are written in the third person singular to emphasize the objective (disembodied?) nature of the scientific endeavour. Traditional science instruction and laboratory practice maintain this dualism and value thinking over feeling. Yet, the idea of affect – emotion and mood – influencing learning is important enough to warrant special issues of the *International Journal of Science Education* (2003, vol. 25, num. 4) and *Educational Psychology Review* (2006, vol. 18, num. 4). Scholars from diverse fields suggest that cognition and emotion are interdependent phenomena (Rosiek, 2003). In her introduction, Elizabeth Linnenbrink notes that all of the authors take the view that there are bi-directional, reciprocal relations among motivation, affect, and cognition. This perspective calls for a dynamic, integrated model in which neither motivation, affect, nor cognition is given

precedence—but rather all three are critical variables for understanding students' educational experiences (2006, p. 311).

Roth and Tobin (2007) note that emotions are central in all social relations and hence in learning, since learning is a product of engaging in activity. Roth (2007a) includes affect within the CHAT model. Through his studies of brain-damaged people, Damasio (1994, 1996) shows how our emotional state affects what we do and how we do it. Science is presented to students as theoretical and technical knowledge, separated from the self and from any ethic-moral sense of acting (Roth, 2007c). Thus, it is even more difficult for students to embrace an identity in science since:

We do not just learn and become scientifically literate for no or some unstated reason—theoretical and practical knowledge in and for themselves, if they are not linked to some emotional valuation that comes with the enhancement on one's power to act, perhaps are not worth being learned (p. 170).

The motive for learning is also irrevocably linked to emotion.

Students' motivation has four components: self-efficacy, belief in the value of the task, students' goal orientation (whether mastery or performance), and affect (Zusho, Pintrich, & Coppola, 2003). Feelings such as timidity, aversion, embarrassment, anxiety, vulnerability, distrust, fear, and self-doubt in varying degrees of intensity inhibit learning (Watts & Pedrosa de Jesus, 2005). Fear can also motivate a student to work hard to achieve high grades in chemistry for premed or engineering (Tobias, 1990). Threat of any kind, including too much information—too new and too fast—causes an automatic

response in the mind and the body to shut down in order to cope with this added stress (Davou, 2002; Perry, 2006). As indicated above, often the lab tries to do too many things with one experiment, overloading the students.

Task value is important to student's intensity of work. Relevance is an essential ingredient to sustain interest in secondary science education (Osborne, 2003) and in tertiary science. A relevant experiment bridges the theory-practice gap, uses familiar loci, and makes sense to the student. Many experiments in general chemistry use chemicals with strange names and fail to relate them to everyday concerns, becoming simply another compulsory exercise to complete. Similarly, student interest quickly wanes with repetition of the same procedure for different variables. Little or no effort is given to providing personal relevance to students' lives, professional relevance to how chemistry applies to possible professions, or social and citizenship relevance for human, environmental, and social issues (van Aalsvoort, 2004a). As alluded to earlier, the goal orientation of many students is to get the highest grade for the least amount of effort. Students in advanced courses who aspire to graduate work seek mastery of the subject and performance is secondary.

Self-efficacy, the belief that one can do well with the necessary effort, can vary from situation to situation. The attitudes of family, peers, and friends can strongly influence efficacy. Students who believe that they are competent generally do well and engage in behaviours that promote learning. Unfortunately as students become exposed to

theoretical and intangible aspects of chemistry, their interest and efficacy wanes (Zusho et al, 2003).

In discussing student attitudes towards science, we must differentiate between school science and science in general (Osborne, 2003). School science is perceived as hard because students find it difficult to get a good grade, it involves a lot of work, and it is often dull and boring (Tobias, 1990). “The fact that only able pupils do physical sciences reinforces the notion that it is for the intelligent and therefore difficult” (Osborne, 2003, 1071). Practical work is not viewed as an opportunity to consolidate concepts taught in class but rather another chore. The attitude of many students is simply follow the recipe, finish as quickly as possible, get the right answer with minimum mental engagement and initiative (Berry et al., 1999).

### *Myths and Beliefs of Science*

Many university students have not yet thought to question their attitudes towards the laboratory and towards science in general. These attitudes often have been unconsciously acquired throughout their life experiences, influenced by peers and family.

Unsubstantiated attitudes may lead to false construction of ideas and impair learning.

Both teaching staff and the students unconsciously adhere to certain myths and beliefs of science tacitly transmitted during instruction (Hodson, 1998). Change is



extremely difficult because both prefer the comfortable and predictable practices supported by the myths. Teachers having the highest degrees were found to be the most traditional in their practice (Roehrig & Luft, 2004). Extrapolating from that, university professors are mired in the belief that knowledge is gained through transmission. Tobin and McRobbie (1996) identified three additional myths held by teachers: the necessity of efficiency, the myth of rigor and the need to prepare students for examinations. Their teaching practices are necessarily affected by their beliefs pertaining to the nature of knowledge and pertaining to the distribution of power (Hashweh, 1996). Students are accustomed to tightly controlled discourse in the classroom and believe that the teacher has the authority and knowledge and that topics must be covered in a timely fashion (Bleicher, Tobin & McRobbie, 2003; Tobin & McRobbie, 1996). Professors, too, are aware of the necessity to manage the course content in the allotted time.

The prevalence of these tightly-held myths generated at least two books to bring attention to them and to debunk them. Henry Bauer (1992) who writes from the perspective of STS—science, technology, and society—directs his work to the general public. He looks at the misconceptions and misleading results surrounding the measurement of scientific literacy, the fallacy of the scientific method (then explaining how science really works), and myths about the nature of scientific facts, theories, and scientists themselves. The book by Morris Shamos (1995) follows the history of science and influence of mathematical proofs from Socrates, Plato and Aristotle. This history sets the context for the evolution of science education and the myths surrounding it.

McComas (1996) addresses myths related to Hodson's (1992) knowledge *about* science. Students view science as a body of uncontested knowledge and believe that scientists can answer all questions if more data is supplied. They are unaware of the limitations and the tentative nature of science. Although these are largely misconceptions about the nature of science rather than the content of science, students carry these false ideas with them to university. In order to graduate as scientifically literate, students' ontological views must be revised.

Much harder to detect and rectify are students' misconceptions on the content of chemistry. These have been identified not only in first year students but also graduate students (Cros, Maurin, Amouroux, et al. (1986); Cros, Chastrette, & Fayol (1988); Garnett, Garnett, & Hackling, 1995; Nakhleh, 1992; Zoller, 1990). Misconceptions may show up as repeated error on the same concept or as students giving up, "I don't understand this" as they try to fit new information on a faulty framework, or try to juggle two different interpretations, one that makes sense to them and one for exam purposes.

### **Learning Theory Espoused by the Traditional Lab**

So far we have seen how laboratories evolved and what influences students bring with them to the lab. What are the characteristics of learning theory presumed by the traditional lab? How do they account for student identity, attitudes, myths, and beliefs of science?

Schooling, including education in tertiary institutions, is based on the premises that (a) knowledge resides in the individual mind and individuals can structure this knowledge to build their own schema or mental structures, (b) schools are neutral with respect to what is learned, and (c) concepts are abstract, relatively fixed and unaffected by the context in which they are acquired (Brown, Collins & Duguid, 1989; Lave, 1993). Knowledge is often seen in the form of a commodity that can be transferred from a more powerful expert to be absorbed by the deficient learner. Understanding would occur when enough facts had been memorized (Tobin, 1996). The professor imparts information, and students learn it; the instructor provides demonstration of lab methods, and the student must magically connect class learning with the experiment. Abstract concepts are presented with the assumption that once the concept is mastered, learners will be able to apply it when and where it is needed (Brown, Collins & Duguid, 1989). This decontextualized knowledge separates what is learned from how it is learned and used and separates the learning mind from the world, confirming the disconnect between mind and body.

In addition to being detached from every day experience, chemistry knowledge is presented from the specialist's rather than the student's perspective (Duschl, 1985). Chemical concepts are not taught in the sequence of discovery but as an expert views them fitting together (Tobin, 1996). Generally, complex ideas are decomposed into simpler parts, often leaving students with mistaken impressions of the absolute validity of a concept. For example, pH is presented as equivalent to, rather than pH is approximated

by,  $-\log [H^+]$ , ignoring the influence of ions, hydrogen bonding, solution chemistry etc. Students memorize these “bits” but cannot fit them together without knowing the expert viewpoint. Learning then becomes processing, storage, and recalling of information.

Science is presented as a *fait accompli*. Students are unaware of the false leads, collaboration, discussions, cultural factors, and ongoing refinement that actually generated the theories and “facts” of chemistry (Bodner, 2003). This is further emphasized in lab work where the results are known in advance and students must produce the expected answer. Thus concepts are presented as abstract, relatively fixed and unaffected by the activity through which they are acquired and used. Little or no effort is given to providing personal relevance to students’ lives, professional relevance to how chemistry applies to possible professions, or social and citizenship relevance for human, environmental, and social issues (van Aalsvoort, 2004a).

Presenting knowledge in this manner reinforces the myths that science and scientists are objective unbiased, unprejudiced, impartial, and logical. Identity, emotion, attitudes, beliefs and myths neither contribute to nor effect what science or chemistry is discovered or taught. Concepts are presented without the history of their development as if they independent of culture, politics, and economics. The culture of science is invisible: the classroom and school laboratory reproduce the cultures of the classroom and school laboratory. Thus, students are engaged in culture of school rather than the culture of chemistry, unconsciously adopting the behaviour and belief systems of the cultural group,

i.e. that of university student. This context-free or society-free knowledge is mirrored by textbook problems and lab exercises that do not resemble real research or industry. Only honours students who are required to do a research project under a professor's guidance, and may also have the advantage of interacting with graduate students and post-docs, have the opportunity to enter the culture of chemistry. By working alongside a skilled practitioner, students acquire the tacit knowledge that is not directly teachable (Hodson, 1992).

### **Chapter Recap and Analysis**

We have seen the development of laboratory instruction from private facilities to funded space as a component of university courses in chemistry. Much current instruction continues to be largely prescriptive in nature, leading to student disengagement. Perhaps the shortcomings are not surprising in light of the history presented. Recall that the students at the Polytechnique in Paris were less than enthusiastic about practical work. Experiments emphasized learning various techniques and often involved repetitious analysis of elements before any interesting work would be approved, and then it often served to further the research of the scientist. As practical work became more widespread, it was often limited by the expertise and interests of the professor of the course. By the time all universities offered laboratory work, practical work served to illustrate concepts taught in class and consequently were largely verification exercises. Such experiments develop the basic skills of observation, measurement, inference, prediction, classification,

and the collection and recording of data; but fail to, or only weakly, support integrated skills of formulating hypotheses, controlling variables, experimenting, identifying problems, defining operationally, formulating models, and interpreting data. Learning, if any in the lab, is based on knowledge transmission and its subsequent acquisition: manipulating lab equipment, collecting data, and perhaps remembering and recalling a procedure.

Examination of the aims of laboratory instruction reveals that they are not met and are poorly understood by the student. In their haste to finish the experiment many students do not have the time or inclination to contemplate how their lab experience relates to the classroom teaching or how it relates to natural phenomena. Perhaps those aims were realistic when all of chemistry could be summarized in one or two books. Today's general chemistry courses attempt to introduce students to all facets of chemistry and expect students to appreciate each one. Overtaxed with unconnected information, the student simply memorizes content in order to complete the course. Similarly, the lab can become a set of compulsory disjointed exercises to illustrate each topic. Laboratory manuals do not specify learning objectives for each experiment or for the course as a whole. Rather, a "purpose" encapsulating what the student will do is presented. A compulsory pre-lab assignment ensures students have looked at the exercise before coming to lab but the absence of a post-lab phase means that students do not have the opportunity to develop deeper understanding of the concepts or methodology (Tamir, 1977). Without the aims and objectives for the lab clearly stated in advance, laboratory work lacks a framework for

choosing the practical work to be done and the most appropriate instructional style for it, lacks organization and structure for learning and hence clarity for the student, and lacks an effective benchmark to evaluate the quality and effectiveness of learning.

The kind of knowledge presented in science is universal, objective, logical and theoretical. The laboratory emphasizes this value-free, rational characteristic. Most undergraduate chemistry laboratories are informed by traditional learning theory with its focus on the cognitive dimension and assume assimilative learning (Illeris, 2003) is taking place. They ignore sociocultural theories of learning (Taylor, Gilmer & Tobin, 2002), accommodative or transcendent learning (Illeris, 2003), transformative learning (Mezirow, 1991), and expansive learning (Engeström, 1987). The next chapter describes these different views of learning and how they can broaden views of science learning and teaching.

## CHAPTER 4: LEARNING RECONCEPTUALIZED

The reason little has changed in practical classes is probably that university teachers concentrate on the experiments to be performed by students and on the time available, rather than on the educationally best way to achieve their teaching aims...although all the evidence that they need to improve practical teaching is easily available (Meester & Maskill, 1995, ¶23).

The previous chapter outlined the nature of science and chemistry instruction from its first incorporation into the university. Today, little has changed in many tertiary institutions from the first methods of teaching. As Richard Duschl (1985) explains, science education and the philosophy of science have developed mutually exclusively with neither group being familiar with the literature and thought of the other. “Individual projects were directed by prestigious scientists, coordinated by advisory boards composed of prestigious scientists, and written by scientists” (Duschl, 1985, p. 547). Yet, the literature contains many articles on alternatives to traditional teaching, and much research into the nature of learning and the specific problems in learning science and chemistry. This chapter examines this literature in order to develop a basis for suggesting positive changes to science instruction and specifically the undergraduate chemistry laboratory to facilitate and support higher cognitive skills and to graduate more broadly scientifically literate students.



## **From Transmission to Conceptual Change and Constructivism**

As seen in the previous chapter, learning is indicated by students' successful recall of what had been transmitted to them by the lecturer. What is learned is separated from how it is known and how it is used, often resulting in students knowing discrete bits of unconnected information. However, research has shown that teaching by telling is ineffective for most students: students do not develop skills of argument, have difficulty constructing a coherent conceptual framework, and often lack connections among concepts, formal representations, and the real world (Bodner, 1991; McDermott, 2001). Ausubel (1968) articulates the idea that the interaction between what students are taught and their current ideas or concepts results in learning. With this thought in mind and the idea of causality from Piaget (Piaget, 1974), many studies on students' scientific misconceptions followed (Driver & Easley, 1978 for example). Posner, Strike, Hewson, and Gertzog (1982) propose a theory of conceptual change to potentially correct these naïve theories. They expand Ausubel's notion to learning as an active process of rational inquiry. Conceptual change—learning—occurs when cognitive conflict causes one to revise or reorganize existing conceptual frameworks to accommodate new phenomena. Conflict arises when new information does not fit into one's current network of conceptions. Students change their conceptual framework when they understand the limitations of their current views and recognize the need to replace them. Pintrich extends conceptual change theory to include motivation (Pintrich, Marx, & Boyle, 1993). The analysis by Duit and Treagust (2003) concludes that teaching informed by conceptual

change is better than the old way but has limitations. First, the focus is on content, even though misconceptions are largely *about* science or *doing* science (see Chapter 1). Thus, conceptual change takes an epistemological view when what is required for scientific concepts is an ontological view. Second, its focus is on the rational, ignoring the affective domain. These two limitations eerily evoke traditional teaching and learning. Lastly, conceptual change omits the social and cultural nature of learning, a much broader scope to the nature of knowledge acquisition. Since research into tertiary education indicates that university students, as well as school pupils, hold faulty conceptions about the content of chemistry (Cros, Amouroux et al., 1986; Cros, Chastrette et al., 1988; Sanger & Greenbowe, 1997; Zoller, 1990), conceptual change continues to be considered for science education albeit somewhat contentiously as seen in the special issue of *Cultural Studies of Science Education* (2008, vol. 3, issue 2) with several authors critiquing either the article by Treagust & Duit (2008) or that by Roth, Lee & Hwang (2008).

Closely linked to conceptual change is constructivism. Science teachers generally hold constructivist views of learning which emphasize that learners, building on preexisting frameworks of knowledge, continuously and actively construct meanings which are subsequently evaluated for acceptance or rejection (Driver & Bell, 1986). The results of learning are structured before they can be retained; “learning from teaching, then, relies on the learners perceiving *connections* between the curriculum content introduced by the lecturer and their existing cognitive structure” (Taber, 2000, p. 65, emphasis in original). This is a positive step forward from traditional learning theory in that understanding

rather than memorization is the goal. However, the construction of new ideas still takes place internally within the learner's head (Millar, 1989). This emphasis on personal construction ignores the social and communitarian nature of science; "it is the 'we think' that determines the 'I think' and not the other way around" (Matthews, 1993, p. 367). Furthermore, the meanings constructed by students may be different from those intended by the instructor. Difficulties also arise in chemistry from alternative models and the interchange of scale: students are unsure of the different ranges of application of the models and which model is appropriate for the context (Driver & Bell, 1986). They also cannot easily comprehend the interrelation among the microscopic (atoms, molecules, particles), macroscopic (things tangible and visible such as phenomena, substances), and symbolic (formulae, equations) meanings of topics and cannot mentally easily switch among levels of meaning (Johnstone, 1991). Maintaining student engagement in order to support the development of a personal understanding of science is difficult when science consists of a consensually agreed upon body of knowledge. Unless the professor encourages class discussion or group work, errors in students' constructions can persist (Tobias, 1993). This shift in emphasis to dialogue naturally leads to social construction of knowledge, from the internal to the external environment in which the student moves (Hodson & Hodson, 1998). These theories are discussed in the next section.

## **Sociocultural Theories of Learning**

The laboratory setting in the first vignette functioned with learning conceived as a process of knowledge transfer. Conventional theories of learning and schooling decontextualized some knowledge and forms of knowledge transmission; just the facts and not their development were considered as worthy of learning. Learning was narrowly focused on knowing or acquiring knowledge and beliefs (Lave, 1996). However, decontextualized knowledge is largely inert. Students can only produce fixed meaning, not understanding, using abstracted knowledge: laws, symbols, and well-defined problems presented in textbooks (Brown, Collins, & Duguid, 1989).

Vygotsky introduced the importance of social relations to cognitive development and the influence of language as a tool for problem-solving (Vygotsky, 1978). In his theory, cognitive development and learning continue throughout the human lifespan, in social interactions, with consciousness. Furthermore, to be effective, education should be learner-centered, active, problem-centered, and cooperative. He proposed that learning occurs thorough collaboration and guidance of peers or educators in what he calls the zone of proximal development. This zone represents the gap between the actual stage of development of a learner and the potential development that can occur in cooperation with others.

From studies of apprenticeship of tailors in Liberia, Lave (1977, 1982) posits that informal learning in apprenticeship is no less coherent and rigorous than formal learning.

Apprenticeship exemplifies integration of process and content, of social and practical, provides a new framework for studying classroom-learning processes and suggests situated cognition, of learning being rooted in the situation in which people participate. Asking what circumstances best facilitate learning, rather than asking what cognitive processes lead to learning was a radical change. Collaboration with Wenger led to the idea of learning in communities of practice (Lave & Wenger, 1991, Wenger, 1998) in which knowing and learning are part of participating in a community. Ourselves and our experiences, the material world, other people and their actions, the power structures, and economic factors form the situation, and the participants in this environment form what they call a community of practice. From Vygotsky's zone of proximal development, Lave and Wenger move to situational learning, continuous learning in our social environment. The individual develops through a movement of participation in a community of practice, perhaps from a legitimate peripheral participant to a full participant as the individual becomes more knowledgeable, or by other interactions such as brokering between communities. Knowledge emerges from the interaction with community, the tools and the activity at hand; knowing and doing are inseparable. However, Lave and Wenger de-emphasize the material components—the tools and artifacts—and emphasize social interactions. In this perspective, appropriation of the language of science and the practices of scientists are important markers of science understanding (Anderson, 2007).

Fenwick's (2000) concept of participatory learning looks to Lave and Wenger. "Individuals learn as they participate by interacting with the community (with its history,

assumptions and cultural values, rules, and patterns of relationship, the tools at hand (including objects, technology, languages, and images), and the moments activity (its purposes, norms, and practical challenges). Knowledge emerges as a result of these elements interacting” (Fenwick, 2000, p. 253). These elements represent echo those present in activity theory.

CHAT posits that learning is activity. Activity systems “are best viewed as complex formations in which equilibrium is an exception and tensions, disturbances, and local innovations are the rule and the engine of change” (Cole & Engeström, 1993, p. 8). Engeström writes that innovative learning or expansive learning involves the “construction and resolution of successively evolving tensions or contradictions in a complex system that includes the *object* or *objects*, the mediating *artifacts*, and the *perspectives* of the participants” (Engeström, 1999b, p. 384, emphasis in original). Resolution of these internal tensions results in a qualitatively new way of functioning for the activity system (Engeström, 2007). The sequence of steps of cycle includes (a) questioning, (b) analyzing, (c) modeling, (d) examining the model, (e) implementing the model, (f) reflecting on and evaluating the process, and (g) consolidating into a new, stable practice (Engeström, 1993, p. 383-4). The cycle begins with questioning accepted practice, initiated perhaps by one person but accomplished through group argumentation, and considers its historicity and its local practice. Including the historical development of scientific knowledge and emphasizing true problems in which the answer may not be known, instruction can encourage classroom or laboratory collaboration and support Engeström’s expansive

learning. However, expansive learning may be impossible in the traditional laboratory since nothing new is being created.

In the same volume, Lompscher considers where shortcomings may arise in activity. “The gap between the necessary prerequisites and the actually existing psychological qualities is one of the main contradictions arising again and again in the learning process (p. 244), one which is continuously solved. The second contradiction lies within learning actions being a prerequisite for the acquisition of certain material, yet they cannot be formed without engaging in the material. “The action’s content, structure, and course are determined by the object” (p. 267-8). This in effect states that an individual or group cannot learn actions without the object; even so, science instruction continually disembodies knowledge from its context. His proposals to accommodate these contradictions include (a) goal orientation, (b) a theoretical orientation towards the inner structure, the essential features and relationships rather than ‘how to’ algorithms (c) systematic formation and mastering of actions, (d) co-operation with peers and teachers, and (e) instruction from the abstract to the concrete (pp. 268-273). These proposals are relevant to science activity. Having clearly defined goals that both the instructor and students understand is also necessary if laboratory work is to fulfill its function as a learning tool (refer to chapter 3). In Tobias’ study of postsecondary science from a sociological perspective, one of the major issues students had was this emphasis on problem-solving without sufficient theory development, the “how” and “why” of decoding problems (Tobias, 1993). We have seen earlier how mastery is beyond most chemistry labs as each week presents new information and new techniques in a new

experiment. Altering lab exercises so that some focus on mastery and others on theory-in-action will improve learning. Social interaction in science is inhibited by individual work in the lab and by little class dialogue, although this is changing. For Lompscher, Vygotsky's zone of proximal development is transformed into a zone of actual performance (Lompscher, 1999, p. 266).

Lemke (2001) examines science education with such a sociocultural perspective.

He writes:

The most sophisticated view of knowledge available to us today says that it is a falsification of the nature of science to teach concepts outside of their social, economic, historical, and technological contexts concepts taught in this way are relatively useless in life, however well they may seem to be understood on a test. (Lemke, 2001, p. 300).

And later:

We are long past the stage in human history when it was useful to artificially segregate the natural from the social world. To study natural phenomena as if *we* were not in society and as if *they* were not interacting with society, through us and through technologies that will amplify and ramify those interactions indefinitely and unpredictably in the human future, is today simply unscientific and irrational (p. 309).

Science instruction has yet to change, persisting in presenting the field from an expert's understanding. What then, does this tell us about science teaching? Lemke suggests that perhaps it is too masculine, too abstract, and too rationalistic and concludes that the culture of science may have to reconsider itself from the perspective of those it wishes to



attract: what identity does it demand from its participants and whether this scientific identity precludes components in other cultures and communities.

### *Transformative Learning*

Paulo Freire, Myles Horton, and Jack Mezirow consider adult learning theory with a transformative perspective. The purpose of both Freire in Brazil and Horton in the Appalachian Mountains of Tennessee was to teach illiterate adults so that they could participate in the political process. Freire notes the political nature of education, that it can reproduce society or it can liberate people from domination (Horton & Freire, 1990).

Changing individuals' thinking and changing their perspective is necessary to changing society (Mezirow, 1997). Transformative learning is profound, challenging, and extensive.

It requires that individuals become aware and critically reflective not only of the assumptions of others, but also of their own. Dialogue is the medium. However, communication can also be culturally distorted and to be effective:

Participants in discourse will: (a) have accurate and complete information; (b) be free from coercion and distorting self-deception; (c) be able to weigh evidence and assess arguments as objectively as possible; (d) be open to alternative perspectives; (e) be able to critically reflect upon presuppositions and their consequences; (f) have equal opportunity to participate (including the opportunity to challenge, question, refute, and reflect and to hear others do the same); and (g) be able to accept an informed, objective, and rational consensus as a legitimate test of validity (Mezirow, 1996, p. 171).

Interestingly, these are also ideal conditions of learning. As Lemke indicated above, the culture of science needs to consider its hidden assumptions and its own self-deceptions, even more so if one of its goals is to develop argument in students (as pointed out in the first chapter). When science is presented as a *fait accompli* devoid of history, students do not witness the progression through alternative perspectives or the challenges and refutations among and between scientists before accepting a new idea. Furthermore, students do not develop critical literacy, wherein critical refers to the ability to see privilege and power. When lab exercises focus on instrumental learning, students do not practice critically reflective thought, do not consider different perspectives to solve problems, and do not engage in interactive and group deliberation and problem-solving. We all need to ask questions of power and advantage in an increasingly globalized world in which industry pretends to be its own watchdog.

### *Transcendent learning*

Knud Illeris posits three dimensions to the process of learning: cognitive (knowledge and skills), emotional (feelings, attitudes, and motivations), and social (communication and cooperation) embedded in a societally situated context. (Illeris, 2002, 2004). Learning incorporates two types of processes, which mutually influence each other, an external interaction between learners and their environment and an internal psychological process in which new learning is connected to the existing cognitive framework (Illeris, 2003). Traditional learning generally ignores the emotional and social aspects of learning, as well

as the external interactions between learners and the constituents of their environment, focusing on internal cognitive processes. Stripping these additional cues disadvantages students in attempts to associate/link new ideas to their existing framework. (In a similar vein, socially situated theories of learning concentrate of external processes, according less importance to cognition.)

In a school situation focus is usually on the learning content...[yet] the value and durability of the learning result is closely related to the emotional dimension of the learning process. Further, both the cognitive and the emotional functions and their interplay are crucially dependent on the interaction process between the learner and the social, cultural and material environment (Illeris, 2003, p. 410).

Schooling encourages what Illeris (2003) names *cumulative* or mechanical learning and *assimilative* or constructivist learning. In either case, students have difficulty applying their learning in different situations. *Accommodative or transcendent* learning, however, involves dismantling and reconstructing one's existing schema in order to accommodate important, valuable (to the individual) new ideas. This is much deeper learning that can be recalled and applied in different contexts. With it comes awareness that one understands the implications and applications of this new concept. Transcendent learning differs from transformative learning in that it is not precipitated by a crisis-type situation. If our goal for students is to be able to understand and apply science concepts, our teaching must aim for transcendent, not instrumental learning.

## **Laboratory Learning**

I have explored learning theories that consider learning more than a psychological function. Now I turn to the literature on laboratory work to determine if and how any changes have been proposed in acknowledging and integrating these more advanced concepts of learning. First, I examine two books about learning in laboratories before turning to the literature on teaching in undergraduate science and undergraduate chemistry laboratories.

## ***Laboratory Research***

Practical work is the only avenue by which students absorb the tacit knowledge or ‘feel’ for lab research (Reid & Shah, 2007; Kirschner & Huisman, 2007). Yet the literature on lab teaching and learning, especially in post-secondary institutions, is sparse and often does not identify this aspect of laboratory work. Latour and Woolgar (1986) sought to determine how scientists work and how scientific facts are created by investigating Roger Guillemin’s lab at the Salk Institute. In the course of their study, they noted many similarities between their particular research of the lab and the research carried out by scientists in the lab. They concluded that research in the social sciences and humanities is not fundamentally different from that of mathematical and scientific research and argue that preconceptions about the “special” character of science need to be re-evaluated. Neither mode of research is inferior or superior, each one produces new learning. This

raises some questions. Do we relate lab learning to other ways of knowing? Do we connect the rigour of lab reports to other report writing for our students? How does university laboratory experience contribute to students being able to work in a lab environment after an undergraduate degree? Are they sufficiently scientifically literate with that training?

The most recent, and perhaps only, book on teaching in laboratories was penned in 1986 by David Boud, Jeffrey Dunn, and Elizabeth Hegarty-Hazel, hardly current given the advances in technology and science in the past twenty-plus years. Yet as they explain in the introduction, the responsibility for lab courses is not normally high status in spite of the difficulty in designing and conducting them, the generally high costs in running them, and the numerous functions accorded them (as explained in the previous chapter). In their opinion, controlled exercises, or conventional laboratories, are suitable to develop basic lab skills and techniques. How one actually presents the work can vary from do-it-yourself demonstrations to audio-tutorial methods. However, incorporating investigation and research projects requires more planning, guidance, and time. Students cannot be abruptly exposed to inquiry activities but require fundamental techniques and exposure to lab problems with steadily decreasing directives. Students learn the value of adequate preparation, and the value of supplementary reading. The authors also consider the debate on the value of laboratory teaching and investigate the literature on research into laboratory work. They conclude that labs at the tertiary level continue to emphasize verification exercises rather than develop the traits of scientific inquiry and processes.

## *Instructional Styles*

The vignette of the typical laboratory I offered earlier exemplifies Domin's (1999b) expository style, using a given procedure having a predetermined outcome and a deductive approach. Guided inquiry or discovery labs change to an inductive approach, providing the procedure and having a predetermined outcome. Students would directly experience a phenomenon and develop an understanding of the underlying principle. This style has its detractors with Kirschner and Huisman (2007) noting that formation of a concept requires multiple exposures to many different instances in a rich educational environment. How then can a single experimental experience be expected to develop this understanding? Hodson (1996a, 1996b) opines that teachers already understand the principles and the underlying theories but "you [the student] cannot discover something that you are conceptually unprepared for. You don't know where to look, how to look or how to recognize it when you have found it" (Hodson, 1996a, p. 118). Using the guided inquiry or discovery style requires careful scaffolding by the instructor and student-instructor interaction. University students need practice recognizing what they are observing.

When students choose their object of research, they may be more motivated to seek connections with prior learning. This is the belief behind inquiry learning in which students generate their own procedure to answer a question with an undetermined outcome, effectively giving students ownership over the lab activity (Domin, 1999b).

Students acquire higher order thinking skills of formulating the problem, predicting the outcome, generating a procedure, and performing the investigation. These skills are required not only for a research-based career but also for the workplace (Garratt, 2002). Students readily experience the importance of careful thinking, planning and interpretation. They must decide what they need to observe, imagine the necessary conditions in order to obtain suitable data, plan, create, observe, and interpret (Garratt, 2002).

Problem-based laboratories use a deductive approach with a student-generated procedure to investigate an undetermined outcome, developing higher order cognitive skills (Domin, 1999b). Problem-based learning has made periodic appearances since the beginning of the 20<sup>th</sup> century, especially in the school environment (Smith & Hall, 1902, DeBoer, 1991). Students gain experience in formulating testable hypotheses and in experiment design. These three styles are all versions of inquiry—inquiry, guided-inquiry (discovery), and open-inquiry (problem-based)—and require more time and resources than the traditional lab. Domin (1999b, 2007) reports, though, that no unequivocal research states one instruction style is more effective than the others. Different styles are better at facilitating different learning outcomes and each style imposes constraints on the instructional environment and the learning process (Domin, 2007). It is important to provide students with opportunities to think, reflect, discuss, and build up aptitude in argumentation. The traditional expository experiment is still useful for the development of

technique (Garratt, 1997) and need not be totally disregarded, but should not be used exclusively to the detriment of higher order cognitive skills.

### *Chemistry Laboratory Instruction*

The sections of laboratory research and instructional styles point to the need to develop student independence from scripted laboratory exercises. I now turn to the literature on chemistry laboratory instruction to determine its areas of attention.

In their chapter on learning chemistry in the lab, Nakhleh, Polles, and Malina (2002), point to the inadequacy of traditional learning theory to account for learning arising from interactions in the lab. Their learner-based model considers CHAT-like interactions in the lab from which they derive some implications for teaching and research. Some have been touched upon in the previous chapter: limited, specific goals for experimental work; practical real-world connections; relevant rather than outdated technology; and repetition of skills and instrumentation to encourage confidence and mastery. They add that students should have sufficient time in the lab to pursue some additional investigations to answer their own questions concerning procedures just learned. They also promote pre- and post-lab discussions.



### *Pre-lab Preparation*

Prior to students commencing lab work, the instructor often gives an introductory talk covering theory if it has not been addressed in class, purpose of the experiment, lab procedures, data handling, and safety. However, dedicated pre-lab time is rare and preparation is done on students' own time (Meester & Maskill, 1993). At a minimum they are required to read the experimental protocol before coming to lab. They may be asked to submit answers to pre-lab questions, to assess safety aspects, to calculate quantities of chemicals required in the lab, or to look up physical properties and structures of chemicals to be used. Getting students to think through the experiment before coming to lab can reduce some of the cognitive load (Johnstone & Letton, 1991).

Further studies on the use of pre-labs show positive results in students' understanding and performance in the lab (Johnstone & Sleet, 1994). For students first experiencing the chemistry laboratory, Rollick and colleagues (2001) require students to submit a synopsis of the experiment at the beginning of the lab and follow it with small group pre-lab discussions to clarify misunderstandings. Motivational factors such as marks increased preparation and hence performance in the lab. An experiment synopsis may be more revealing than a requirement for background information since students must be more concise and consider carefully the relationship between procedural understanding and conceptual understanding. Since "what we already know and understand controls what we learn" (Johnstone, 1997, p. 266), adequate preparation is essential for valuable lab learning. Furthermore, Johnstone (1997) reports that students who did a fairly comprehensive pre-lab had fewer thoughtless questions than unprepared students.

It appears that the time delay between the pre-lab and actual performance of the experiment may contribute to students' understanding. Jalil (2006) investigated whether this discussion is best given after students do the experiment rather than before and concludes that although it is difficult at first, most students in his study prefer to conduct lab work before it is explained to them, thus developing initiative and self-confidence. Isom and Rowsey (1986) reported significantly improved academic performance in general chemistry with a pre-lab preparation period of forty-five minutes one to two days before the lab itself when dealing with unfamiliar concepts. Pogacnik and Cigic (2006) also sought to motivate students to study before coming to lab. In their model, instruction on the theoretical basis of the experiment and data manipulation is given well in advance of the lab. This is followed by a lab quiz given at least a day prior to the experiment day. To balance the increase in time spent in preparation, shorter reports were written immediately after the experiment. The actual pre-lab discussion led by the instructor could then include misconceptions made apparent from the quiz answers and simply manipulative and safety details of the experiment. This method would reduce cognitive load, prepare students, and increase discussion within the lab community. This concept, while successful among non-major students who required chemistry for their program of study, may be more problematic to apply to chemistry majors and their multiple lab requirements. However, it does suggest a method to motivate and instill good lab habits for general chemistry students and to support collaboration within the class. Reid and Shah (2007) recommend pre-lab instruction to share the aims of the experiment, establish the background, to

stimulate, encourage and verify students' conceptions, and to plan the experiments. In this manner, the pre-lab can bridge the lab-lecture gap.

#### *Post-lab Instruction*

If Pogacnik and Cigic's pre-lab preparation is unfeasible, perhaps extending post-lab interactions is desirable. Unfortunately at the university level, post-lab discussions are generally limited to questions posed in the lab manual to be answered in students' written reports and to comments written on the student's assessed reports. Very rarely is there a post-lab discussion to develop deeper understanding of the theoretical implications of the lab exercise (Tamir, 1977), or the processes and techniques learned (Kirschner & Meester, 1988). Post-lab discussions can address confusion about the lab, develop a deeper understanding of the relationship between the theory and practice of the lab exercise, consolidate concepts, and introduce real world applications of the skills learned in the experiment (Reid & Shah, 2007). Johnstone and Sleet (1994) advocate mini-projects in which students devise their own procedure based on prior lab exercises. These exercises would also develop cognitive skills that go along with students engaged in experimental design and planning. Nicholls (1998) employs post-labs for data analysis. Students see where their datum lies within all the results obtained and learn the principles of data manipulation. Usually students have only their own data from which to support their argument and draw conclusions; post-labs of this type are a decided advantage over statistical problems in texts.

### *Computer Aided Instruction*

Computer simulations can also serve as pre-labs or design aids. Computer videos to demonstrate basic lab skills give students a front row seat to review procedures and manipulations as often as required. At Liverpool John Moores University, students are required to successfully complete computer pre-lab programs with a minimum mark of 70% in order to gain entrance to the lab (Nicholls, 1999). Students can work at their own pace and are allowed to repeat the pre-lab until they are successful. Winberg and Berg (2007) offer a computer-simulated pre-lab to reduce the cognitive overload of lab experiences and to highlight what really matters. The focus on theory central to the experiment in the simulation shifts students' perspective toward more theoretical and reflective questions during the exercise. Improved understanding results in greater efficacy. Kirschner and Huisman (1998) consider the use of "dry laboratories" or computer simulations of experiments to support and enhance cognitive skills. These may be useful in designing experiments, in testing and justifying scenarios, in performing impossible or impracticable experiments, and in understanding processes. However, Garratt (1994) cautions that simulations are not suitable for introducing students to new theory.

### *Improving Concept Development*

We have seen how the laboratory focus on doing rather than on thinking is to the detriment on conceptual understanding. Two useful heuristics can be applied to address this deficiency: Gowin's Vee (Gowin, 1981) and concept mapping (Novak, 1984). Gowin's

Vee diagram illustrates the interplay between theory and practice with theory or conceptual ideas on the left side of the Vee and practice or methodological claims, records, and data presentation of the right side of the Vee. Questions or problems being examined lie within the Vee itself and events or objects at the apex of the Vee. This helps students see the relationship between concepts and methods, between what they believe with what they see in the lab. The questions answered by this diagram are: “(1) what is the ‘telling question’? (2) What are the key concepts? (3) What methods of inquiry (procedural commitments) are used? (4) What are the major knowledge claims? and (5) What are the value claims?” (Novak, 1986). The Vee diagram is also useful checking lab protocols to determine what concepts are needed in order to understand the experiment (Nakhleh, 1994).

Concept maps indicate hierarchic relationships and crosslinks from a key concept through component concepts and specific concepts to examples. By this visual representation of connections, concept maps can identify errors and omissions in students’ knowledge relevant to each experiment. These heuristics can be used singly or together to improve students’ understanding of how practical work is informed by theory.

In summary, for deeper learning to occur, lab instruction cannot begin and end at the lab door. To decrease cognitive load students must come prepared having done more than simply reading over the procedure. The degree of pre-lab preparation is somewhat dependent on the instructional style and the post-lab requirements. Used correctly, computer aided instruction can enhance all stages of laboratory work, for example, “how

to” video clips for new methods, in-lab scrutiny of standard curve data, and post-lab extensions. However, students must be motivated to take advantage of a rich learning environment. Motivating students requires knowledge of other factors influencing science learning such as language, affect, and attitudes was discussed in Chapter 3. I now become more specific to clarify the relationship between the lab environment and student identity and how the nature of that association can facilitate the learning that takes place.

## **Other Factors Influencing Science Learning**

### *Identity*

We need to organize learning environments and activities that include opportunities for acquiring basic skills, knowledge, and conceptual understanding, not as isolated dimensions of intellectual activity, but as contributions to students’ development of strong identities as individual learners and as more effective participants in the meaningful social practices of their learning communities in school and elsewhere in their lives (Greeno et al, 1998, p. 17).

Chickering and Reisser (1993) noted that the college years are important in the continuing process of identity development. Students’ identities are shaped by the practices in which they learn (Greeno et al, 1998). Exposure to traditional and cognitive theories of learning leads to (by and large) unmotivated students who memorize information and perhaps have acquired general conceptual understanding. The authors propose a situated perspective to integrate the behavioural and cognitive approaches to learning within a social practice.

Identity, motivation, and emotion are integrally related (Roth, 2007a). Students' negative feelings about lab work often are associated with negative feelings about themselves. Students feel a tremendous amount of self-doubt, especially in their first year of university and this influences their lab work. These feelings are exacerbated when experiments are too difficult, too long, or too conceptually complicated (Bliss, 1990). However, the corollary is also true: good lab experiences generate feelings of achievement, responsibility, and satisfaction. Because emotions interact on three levels—individual, unconscious, and collective (Roth, 2007a)—one disaffected student can disrupt the atmosphere in the laboratory setting, interfering with everyone's learning.

Bracher writes about interferences with learning in the three different identity registers mentioned in the previous chapter. Learning is facilitated if it elicits an identity-bearing affect and it is inhibited if the content or the process evokes a threat to identity (Bracher, 2006). Students bring their unresolved negative classroom experiences with them to university. Even the physical appearance of the lecture room or laboratory can place a barrier between the instructor and the students, a form of subtle intimidation and subliminal messages. What appears to be straightforward questioning or responding can threaten identity and emotion—if the question is considered 'dumb', or the answer is incorrect, the student may feel the cost is too high to their identity as 'smart' (Watts & de Jesus, 2005). Students participate in many activities or communities and become adept at 'code switching' (Roth et al, 2004). However, if the activity of science threatens their basic

cultural identity, students may become disengaged and disbelieve they could possibly be a scientist (Barton, 2000; Brown, 2004).

The process of becoming a chemist is through “participatory appropriation” (Rogoff, 1995). Individuals change through their involvement in the community of students of chemistry, chemistry professors, and researchers; participation in activity prepares them for later activities. However, professors and instructors of chemistry (and science in general) would be wise to remember that “concepts and meanings that are available...but cannot be related to experiences and thus are not given a personal sense, will not become part of the identity configuration” (Geisel & Meijers, 2005). Ideally, science graduates would have sufficient experiences in chemistry that they can cope with new situations and apply their learning in the workplace.

### **Chapter Recap and Analysis**

This chapter has considered various theories of learning, each of which has important contributions if we are truly serious about enhancing science learning and understanding at the tertiary level. From conceptual change theory and constructivism we have learned the importance of verifying student conceptions and understandings. An incomplete or erroneous foundation seriously hinders learning and cannot support increasingly complex concepts. Sociocultural theories of learning argue against the dualisms and narrow concept of learning and knowledge proposed by traditional theories, focusing instead on interactive



systems. Individuals learn through social interaction and socially supported interactions, using what they already know to construct new understandings. Thus, learning is rooted in the milieu in which a person participates, not in the learner's head. Prior experiences and culture, and the emotions associated with them are brought to each learning situation. Learning is the process of becoming, of crafting one's identity in activity with others (Lave, 1996). Transformative learning develops habits of mind indispensable to analyzing situations in which decisions based on science impact every day life.

These messages are more easily accommodated in the laboratory by choosing a variety of Domin's laboratory styles rather than just the traditional one. Different types of knowledge require different instructional strategies. Regardless of the instructor style, students must prepare for the lab, not only to decrease the heavy cognitive load of the lab, but also to support understanding and learning from the experience that goes beyond repeating a prescribed exercise. Various pre-lab activities have been studied, all indicating enhanced lab performance. How an instructor or department proceeds will depend on the numbers of students enrolled and the available resources. Post-lab exercises or discussions consolidate learning and can bridge the theory-practice gap. Furthermore, they provided a forum for critical questioning.

Do we train our students to ask questions such as: Are these decisions favourable to industry to the detriment of the environment? Beneficial in the short-term and disadvantageous in the long-term? Who finances the research behind this claim? These are the types of questions a critically scientifically literate individual will be concerned about.

In the next chapter I present a reconceptualized laboratory considering the research on learning discussed here.

## CHAPTER 5: THE RECONCEPTUALIZED LABORATORY

Chapter four presented other perspectives of learning that would accommodate students' conceptual, identity, and social difficulties with traditional science instruction. How would the chemistry laboratory be organized and arranged if it considered these ideas and research? As indicated in the research, different activities would fill the available lab slot. Some time would be given to acquiring manipulative skills, perhaps followed by applications of these methods and skills. Other time may include investigative work, demonstrative work, and confirmatory work including statistical analysis. Experiments would progress from simple skills training at the beginning of the course to complex student-centered inquiry as students gained sufficient theoretical understanding to pursue such inquiry.

How would such a laboratory appear under this system? Imagine this scenario taking place in a university chemistry department. Every other year for the last month of second term, the chemistry laboratories combine their analyses on one investigation. (In the intervening years, students choose a topic that they wish to pursue.) Instead of individual experiments, they are part of a multi-level study. This year the study centres on energy drinks as suggested by last years' students. This study would expose students to the type of work done in other chemistry courses, collaboration with peers, research into methods, trial and error, and to an open-ended exploration. The lab instructors worked

over the summer to look at the feasibility, possible chemicals and equipment required, ordering, and division of course and year-appropriate investigations. For example, general chemistry students were tasked to determine how much sugar was present in three different brands of energy drinks, and organic chemistry students the amount of caffeine in the same brands, etc. Data from each study was pooled. First year students had the results of sugar content from every lab section so they could calculate the average amount of sugar present and do a simple statistical analysis. They were also given the averages and statistical data (more comprehensive at higher levels) from the other studies.

This laboratory is quite noisier and busier than Chris and Pat's lab in Chapter 2. The class discusses as a whole and in groups what they know about energy drinks and how they might sample them for the study. The students are given their topic but they must decide on their own predictions, methodologies, and how they will share the work. They work in groups of three to five; a larger group may have two different brands of energy drink whereas a smaller group may have only one. Each group writes a report using the combined data (and methodology) from all the experiments on the same analysis. From the pooled data of all the variables tested, students decide what they think about using energy drinks. All of the students have an opportunity to meet together in an auditorium, hear the results and recommendations from each spokesperson, and ask questions. Before the end of term, each student will anonymously offer their evaluation of the study and suggestions for another departmental project.

While what follows is a predicted best-case scenario. In my experience this picture is realistic of students gradually acclimatized to taking responsibility for their lab activity. Normally students dislike group work; however, the millennial student is peer-oriented and group-oriented which overcomes some of the problems inherent in group activity. The vignette below follows the conversation of a group of students tasked to determine the caffeine concentration in two different brands of energy drinks:

Terry: Can't we extract the caffeine the same way we did for tea?

Jordan: What happens to all the other chemicals? Are they soluble in the solvent?

Terry: But tea had other chemicals too.

Jean: The sugars are water-soluble and they are present in the greatest amount.

Kelly: How can they? They aren't first on the list of ingredients.

Jordan: True, but look at how many different sugars are on the list.

Terry: Okay, so as long as sugar isn't soluble in our solvent we can try to extract caffeine the same way. Then what happens to the ions—the Ca, Mg, etc.?

Jean: Instead of trying to precipitate the caffeine, why don't we extract it and run a sample through the GC?

Kelly: Then we need to run standards so we know how much caffeine is in.

Jordan: Yeah, and that will solve the problem of contamination.

Terry: Let's hear what the other groups decided and maybe we can do both methods and compare them.

Kelly: The instructor is sure to like that idea.

Jean: And if the GC has the flu again, we have a back-up method. (Laughter)

...

*Three weeks later the students have all the information.*

Terry: Look at the amounts of caffeine in these drinks! Talk about a jolt.

Jean: I prefer mine as a java jolt. (Laughter)

Kelly: So who drinks this stuff anyway?

Jordan: Ever go down into the gym? Some of the athletes say it keeps them going.

Jean: But look at the amount of sugar in them as well.

Terry: Don't both of those provide a short burst of energy and then a let down?

Jordan: I think sugar has more of a letdown. I just get tired when the caffeine wears off

but maybe that's because I'm up too late anyway.

Kelly: So how are we going to present all this information?

Terry: Well, we have three different drinks and data on caffeine, sugar, ion content, total calories, and protein.

Jean: When muscles work long and hard, what is being used up that causes the cramping?

Jordan: There's a start. For drinks to be effective, they need to replace liquid and ions.

Kelly: Okay. Let's make a table of drinks and what is in them.

Jean: Then we can see at a glance the differences and compare them.

Jordan: Back to our prediction...

Kelly: We can discuss what is in the drinks, why they (advertisers) claim they are so good for you, what we really need when we work out on a hot day...

Terry: Maybe change the order to read better.

Jean: So, we bought into the hype of energy drinks and I get the feeling that we disagree with our hypothesis. Any opinions?

Others: Yeah... Yup... Sure...

Kelly: You're better off drinking water. It's cheaper too.

Jean: But when you sweat, your skin is salty.

Jordan: So, eat more salt. (Laughter) No, seriously, people who live in hot climates eat more salty food than I do.

Terry: Would anyone here ever recommend these drinks?

Jordan: You can get stuff for dehydration in the pharmacy that effectively replaces lost minerals. Wouldn't that be better since it doesn't have the caffeine and the same sugar?

Kelly: Good idea!

Jean: Who is going to present this to the seminar when we all get together?

Terry: Let's first get our data, discussion, and recommendation written. Then maybe whoever feels most comfortable with all the points can present it.

Perhaps the most noticeable difference between this scenario and that presented in Chapter 2 is that the students are totally concentrated on their work. Their conversation centers on the task at hand and brings in knowledge from previous lab work as well as from everyday experience. They intersperse the necessary scientific terms in normal speech; everyone understands the language and terminology used. Their discussion demonstrates awareness of some pitfalls in scientific work: interference by other species

and unavailable equipment. They realize the need to present their data effectively for analysis and to relate it to the body's physiological needs in order to support or counter the claims made by advertisers. In many ways, these students exhibit many of the traits of the critically truly scientifically literate. To further corroborate this claim, I turn to a CHAT analysis to probe the interactions and their meanings.

### **Analysis of the Reconceptualized Laboratory**

This lab class is poles apart from the conventional undergraduate laboratory. Rather than one three-hour period, the study on energy drinks takes one third of the allotted lab time for the term and challenges students to consider all the processes they have learned, to choose something suitable, to modify it to generate a procedure for this analysis, and finally to test it. There is no recipe. Students combine their knowledge, search for references, and consult their classmates, the instructor and/or demonstrators. There is no predetermined "right" answer; No one really knows what the results will be and students may have different opinions for different reasons using the same data. Yet these students are similar to those in the first scenario, from different cultural backgrounds, with different educational background, different expectations and goals, different beliefs, different motives and different learning styles. This CHAT analysis follows the same arrangement of components of the activity system as that in chapter two.



### *Components of the lab activity system*

#### *1. Subject of activity—the student group.*

The students present in the reconceptualized lab display a maturity lacking in the original vignette. Rather than discussing their social life, they are intent on solving the problem presented, perhaps more so since they can relate to the chemicals in question and the product containing them. In doing so, they respect each other's feelings, misconceptions and knowledge. It is simply stated that because there are many sugars present in the energy drink, sugar does not have to be first on the list to be present in the greatest amount. Laughter is directed towards a non-functioning GC or towards an individual who invites it while still remaining on topic (i.e. not clowning around). Whoever feels most comfortable once the analysis is complete will present the group's results. The conversation contains scientific terminology—for example, extract, soluble, solvent, GC, precipitate, and standards—that everyone understands. Students have had sufficient practice with using the vocabulary and concepts behind the words and are relaxed in their identity as “chemistry student” or “chemical investigator”.

#### *2. Instruments/Tools/Inscriptions of the chemistry laboratory activity.*

A wide variety of tools is suggested here. Besides general equipment and glassware, students are using instrumentation, the GC, and probably computer graphics and statistical packages. Also, they are using science terminology to discuss science processes. Conversation suggests that they are sketching out ideas with pen and paper before

committing to an electronic version. In doing so, students are also tapping into their combined knowledge, both formal and informal, and applying it to this problem. They refer to previous experiments, and possible interference from different components when coming up with a method of analysis. They also consult other groups and the instructor. Data from other lab sections and other lab courses are yet another tool in their inquiry. Presenting their results in a table in such a manner as to best support their argument implies that they are familiar with inscriptions of this type as well as the proper use. This is remarkably different from the traditional lab wherein the two students worked alone, talked of their social life, and left as soon as possible without seeking advice from anyone with their errant data. Chris and Pat appeared at a loss to deal with the standard plot and did not relate it to anything they had previously learned whereas this group of students was prepared to use all the available tools.

### *3. Object of activity.*

The initial object of the activity is to devise a method to determine the amount of caffeine in energy drinks with the goal of forming an opinion on the use and/or need for energy drinks on the basis of the collected data from all of the studies. The actual hypothesis or goal was left to each student to determine. Some compare the lost liquid replacement of energy drinks to water; some may consider lost ion replacement, etc. There is no correct answer, but rather engagement, discussion, and argument supporting one's hypothesis. The students are absorbed in the experiment, unknowingly accomplishing secondary goals set by the instructor for collaboration, for research as a scientist would,

for argumentation, and for communication. In doing so, they are developing traits of the scientifically literate. This exercise of *doing* science (the object of the activity) involves knowing science, knowing about science, and considers the social/economic use of energy drinks. The discourse of the students indicates traits of “true” scientific literacy and the beginnings of critical scientific literacy.

*4. Other components of the activity system.*

The rules of the course and institution have changed very little from the original discussion in chapter two. However, the lab environment is much more flexible and relaxed, the tacit understanding is that each student contributes to the overall study and does their share of the work.

That a community of learners and investigators are collaborating and interacting is very apparent. There is interaction among groups in the same lab, with the instructor, and among other classes. This multilevel contact and communication serves to “fuzzy” the division of labour and hierarchy. The students are working together on a study, combining their knowledge not competing. The instructor facilitates. Because assessment is required (under rules), the instructor occupies a position of some power. Since there is no predetermined answer, the instructor no longer is seen to be all powerful, but a resource and a peer. All participants contribute, as they are able.

## **Comparison of the Reconceptualized Lab with the Traditional Lab**

The laboratory originally described in Chapter two exhibited some interesting contradictions. Has this reconceptualized lab resolved any of these issues? Or has it produced contradictions of its own?

Engeström's primary contradiction within the student of grade-maker versus sense-maker (Engeström, 1987) appears to be resolved. The students within the group are absorbed in their task, applying their knowledge of chemical analysis to generate an appropriate procedure. Later when all the data is available, they evaluate the meaning of the results. Making sense of the combined analyses requires integration of many different skills, a task in which the entire group seems readily able to contribute. In contrast, Chris and Pat went through the motions of their lab experience and applied little if any knowledge, having learned tacitly that the requirement was simply to complete the experiment and hand in a report.

As the literature has amply shown, the general goals, aims, and objectives of the lab must be clear to students if they are to take full advantage of the learning opportunities presented by the laboratory. Some of the detachment in the first vignette can be attributed to poorly designed goals or to too many goals for the same exercise (learn to make standard solutions and a standard curve, learn to use a spectrophotometer, and use the methodology to determine the value of the unknown). The goals of students in a

traditional lab are to do the experiment as quickly as possible and to get the best mark for the least effort; the goals of the experiment and the instructor are not even known or considered by many of them. In the reconceptualized lab, the students had a defined objective to create a procedure to determine the amount of caffeine in a liquid and then to apply it to energy drinks. The broad goal for the study, to decide how they felt as individuals on the use and/or need for energy drinks, was interesting and relevant enough to keep their attention over the length of time allotted for the work. The outcomes are probably apparent to the students: collaboration, scientific attitudes, confidence, and enjoyment.

An examination of Engeström's other primary contradictions (Figure 2.1) indicates resolution as well. The students are aware of the necessary tools, instruments, and inscriptions and use them well. The community expanded to accommodate various levels of activity. Initially, students arranged themselves into teams of inquiry; they consulted with other teams in the class and with the instructor; they collaborated with other sections of the same analysis; they combined results with other sub-disciplines that performed different analyses. Collaboration also served to moderate the division of labour. No longer were they working as individuals; knowledge was not simply a property of the individual, but emergent from participation of everyone within the group.

Then what of the contradiction of between production and consumption? The cost of science laboratory instruction results in higher tuition for science students; how

can quality and cost recovery be balanced? Consider the qualities of scientific literacy for the university science major outlined in chapter one. It is evident that the exercise undertaken in the cause-and-effect lab contributes little to the development of those skills. In this case, the cost to benefit ratio is high, especially bearing in mind that the students did not emerge even with an understanding of the procedure. In the second scenario, there is application and consolidation of knowledge as well as growth in attributes of the “truly” scientifically literate and the critically scientifically literate. These advantages add greatly to the quality of the experience (probably for no extra cost given that only one, not four, experiments are undertaken) resulting in a much lower cost to benefit ratio, pleasing the students, the department instructors and professors, and the university administration.

### **Further Examination of the Reconceptualized Laboratory**

This experimental investigation not only entailed student initiative, engagement, and commitment in order to be successful, but also careful course planning to develop the manual and cognitive skills of the students prior to the study. Incoming tertiary students whose exposure is limited to controlled experiments require exposure to problems with steadily decreasing assistance (Burke, 1979) to build their skills and confidence in order to deal with investigations of this type. First year students would most likely modify a procedure already done in lab for a different substance, revising it where necessary; for example, rework the protocol to determine the sugar content in regular and diet pop to determine the sugar content in energy drinks instead. The group of (second year) students

in the vignette recalled a previous experiment in which they extracted caffeine from tea and suggested using another technique, a GC analysis, as well. Students at all levels will increase their competence in the methodology of choice, in the subsequent data interpretation, in oral and written communication, in applying their personal attributes such as imagination to problem-solving, and in interpersonal interactions. These skills are applicable to a wide variety of chemistry and chemistry-related fields. The reconceptualized lab begins to incorporate some of the theory discussed in chapter four which has shown that student learning is enhanced in shared, collaborative, relevant learning experiences in which students take an active part. In Chapter 6, I discuss implications for laboratory work and suggest further study.

## CHAPTER 6: CONCLUSION

This thesis has shown that the “cookbook” undergraduate chemistry laboratory fails to meet the expectations for learning. A CHAT analysis undertaken in chapter 2 indicates prescriptive exercises do not provide a suitable framework in which students can build on their understanding of chemistry and begin to develop scientific attitudes. Such practical work exemplifies the traditional learning theory informing it, in which regurgitation of material is an indicator of learning. From an examination of contemporary learning theory, an alternative vision of the laboratory was presented. Its subsequent analysis demonstrated increased student participation, comprehension, and skills. Reformulating the lab does not require major structural changes but rather ontological changes on the part of the instructors involved. Rethinking pedagogical practices, reworking pre-lab exercises, and rewriting lab manuals to reflect this new ontological vision requires time, energy, and support, especially since traditional practice is so automatic. Change is difficult and the next section considers this briefly; an awareness of barriers is essential for the successful transformation of the laboratory into a rich learning environment. I then discuss implications for the undergraduate lab and conclude with suggestions for further study.

### **Changing the laboratory**

How we understand learning has progressed from knowledge transmission and reception with its consequent change in behaviour to making meaning with others in the context of



everything we do. Learning is no longer thought to reside in the individual but is distributed among individuals, social relationships, the tools and artifacts that they use, their culture, and their history. This, however, has not translated into revised teaching and laboratory methods in tertiary institutions (Spencer, 2006).

A laboratory component is an accepted part of the science curriculum, albeit somewhat contested in terms of its effectiveness. It is through practical work that students “absorb” the tacit knowledge or *feel* for lab work that cannot be instilled any other way (Kirschner & Huisman, 2007; Reid & Shah, 2007). Although few students who take chemistry become scientists, it is important that they are aware of the limitations of experimental work (Byers, 2002; Schwartz, 2007). Since the laboratory component is expensive and time-consuming, it should provide a positive and meaningful learning experience.

However, as discussed in earlier chapters, most current tertiary lab instruction persists in utilizing essentially didactic exercises. Introducing change is not easy with both cultural and political barriers strongly resisting (Taylor, Gilmer, & Tobin, 2002). This thesis has shown that scientific discourse is an obstacle for students and can be used to emphasize the power professors wield. This patriarchic, Euro-centric, middle-class discourse can also alienate others by gender, culture, class, and economic status. Professors and instructors cannot transfer knowledge or even their enthusiasm for their subject or learning in general. As Mark, a university chemistry professor stated, “I have to

help the student find some reason that this material is interesting or relevant. I can't transfer my interest or sense of relevance to other students. They have to construct it for themselves." (Abbas, Goldsby & Gilmer, 2002, p. 189-190).

Change is not conflict-free. Not only faculty, but also students are resistant to change and can become very frustrated when expectations are revolutionized from the old transmission method. No longer can they be passive receivers of knowledge, but they must be actively engaged in constructing that knowledge, taking the time to struggle with unfamiliar material. Some students view this as professors not doing their jobs. Students for whom chemistry is a required course for related studies may react more negatively. Instructors must be aware of student frustration and manage it carefully (White, 2002). It must be safe for students to admit that they do not know the answer, to recognize, define, and learn what they do not know.

Local change in lab courses is only a beginning in changes that must eventually revolutionize classroom teaching as well. Prospective teachers will likely reproduce the same teaching styles under which they themselves learned the science at university. For teachers to change their instruction style, university science professors and instructors must change their instruction style. A large impediment is that instructors and professors are not aware of learning theory, or of improvements to understanding how adults learn. They come to university and college teaching with no training in teaching and must discover for themselves what seems to work best with their students, often mimicking

their own preferred method of learning. Perhaps already overloaded with work, it is best to leave the lab as is since that is the way it has always been. As Tobin noted, the trend for chemistry profs “was to teach through better transmission of information” (Abbas et al, 2002, p. 200). Reform at the university level requires a critical mass from peers and positive student evaluations supporting it against the naysayers, who may include a cost-conscious administration and other professors and instructors. There is a resistance to any decrease in content, but a decrease in content is necessary in order to enhance students’ thinking and expand their ways of knowing. The benefit is confidence in their own ability to think and learn on their own. Yet professors continue to value chemistry content and resist change (Mabrouk, 2005; Tobin, 2002 In Taylor, Gilmer & Tobin). The critical mass necessary for reform is often missing in universities. Students support in evaluations and their demands for reform are essential to set change in motion.

### **Implications for the Laboratory**

What level of scientific literacy do we want our students to achieve? Before any comprehensive reform can be considered, the expectations for a lab course must be defined first in terms of the program in chemistry as a whole, then for each year, and finally for each course. In this manner, there will be a progression of all skills and lab experiences consistent with the specified skills (Reid & Shah, 2007). Thus, students who major or minor in chemistry will be certain to have experiences relevant to their level. No longer is the rationale “we have always done it this way”; but “does this experiment meet

our criteria for inclusion?” Clearly stating the aims (intention of the experiment from teacher’s perspective) and the objectives (what the student is able to do after finishing the experiment) for each practical is beneficial to the instructor and the student.

Clearly defined aims and objectives also assist in planning relevant pre-lab exercises. Pre-lab preparation is essential for learning, not only to reduce cognitive load, but also to prepare the student mentally; previous learning influences how and what the student observes in the laboratory. The objective is to slowly wean students from prescriptive manuals towards asking themselves what they need to know and prepare before the lab. Here the greatest hurdle is to convince students to prepare. Giving students greater autonomy and ownership over lab work and making lab exercises relevant are not only positive incentives, but also benefit students’ efficacy, responsibility, and confidence, their science identity, and by extension, their level of scientific literacy.

Different types of lab work have different goals; it is necessary to mix them and use them at the appropriate time. First year undergraduates generally are not ready for student-led investigative experiments. Controlled short activities, much like the traditional lab, devised by departmental staff are suitable to teach lab skills, the use and manipulation of lab equipment. These really ought not to be assessed for knowledge but for facility, perhaps when the student feels competent. “A carefully thought out skills program that allows for frequent reinforcement” (Johnstone & Letton, 1991) so that students are not trying to master new manipulative skills along with new instrumentation and procedures. Lab time

could easily be dedicated to this purpose. Once students are comfortable and competent with a procedure, applicable experimental work can follow.

To support relativistic views of knowledge, investigations which require student decision-making and reasoning with evidence need to be part of the lab curriculum.

Different types of exercises can be employed to create interest such as:

- Problem based learning, with real-life based, current controversies,
- Repeating a procedure from a research article,
- Group work in which students choose their own problem, devise a procedure, make predictions, follow their protocol, and present the results to the class, or
- Using accumulated class data to introduce statistical techniques, error analysis, and their application in argument and discussion.
- Allowing students choice from a selection of experiments.

Rosalind Humerick's (2002) students all agreed that most lab learning occurred in the lecture hall. This suggests that students are simply following the "cookbook" and making sense of it later, if at all. Changing to learner-centered teaching and inquiry labs helps stimulate student thinking and gets them to work out an answer. Requiring students to include a short statement what concepts they learned and how they were illustrated by the exercise, what experimental techniques they used, and where the main experimental errors lie causes them to think beyond the mechanics of performing the experiment. Introducing a gradual progression in lab complexity and student self-reliance is a common theme; the

instructor becomes a facilitator as the student becomes more adept. The student practices and slowly acquires the skills and questioning mind of higher levels of scientific literacy.

All of these implications fall flat unless the issue of language is addressed. It is important to make connections with the experiences, language, and every-day world of the student and to maximize participation and interaction among students so that they can negotiate meaning and understanding and acquire scientific vocabulary in context.

### **Suggestions for Further Research**

Incorporation of these recommendations into lab courses is the natural next step. I have offered students in a qualifying year course alternatives in their practical work. The concluding investigation to answer a chemistry question sparked by their curiosity was highly successful. However, these were largely mature motivated students. We need to wean traditional students from didactic instruction.

Initially, aims and objectives must be decided. How can a lab course be successful if we are uncertain of the reasons for it? A survey of first and second year course instructors and professors to determine what laboratory skills and knowledge are expected after one year of university chemistry is the first step. The first year lab manual would then be modified to support these aims and objectives. Each subsequent year, another level of labs would be revised. Student learning can be tracked under the new system

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